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EVALUATION OF THE EFFICIENCY OF INDUSTRIAL FLARES:

Background - Experimental Design - Facility

by

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Flames				
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ABSTRACT

The U.S. Environmental Protection Agency has contracted with Energy and Environmental Research Corporation to conduct a research program which will result in the quantification of emissions from and efficiencies of industrial flares. The study is being conducted in four phases:

I - Experimental Design

II - Design of Test Facilities

III - Development of Test Facilities

IV - Data Collection and Analysis

This report provides the results of Phases I and II of the study.

The report summarizes the technical literature on the use of flares and reviews available emission estimates. Technical critiques of past flare efficiency studies are provided. Mathematical models of flame behavior are explored, and recommendations for flare flame models are made.

The parameters affecting flare efficiency are evaluated and a detailed experimental test plan is developed. The design of a flare test facility is provided, including details on the flare tips, fuel and steam supply, flow control and measurement, emissions sampling and analysis, and data acquisition and processing. A Quality Assurance/Quality Control Program is also described.

Results of the testing program (Phases III and IV) will be included in a later report.

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TABLE OF NOMENCLATURE

Variable Symbol	Meaning
A	Cross-sectional area
b	Characteristic jet radius
C_E	Local entrainment coefficient
C_s	Spread coefficient
C_L	Flammability lean limit
c	Concentration
c_p	Specific heat, constant pressure
C_v	Specific heat, constant volume
D	Distance
DE	Local fuel destruction efficiency
DF	Dilution factor
d	Diameter
E	Global emission, $E = 1-U$
F	Fraction of heat released in a flare that is radiating
FRG	Federal Republic of Germany
FR	Froude number
f	Eddy generation frequency
$\dot{G}$	Jet momentum flux
g	Gravitational acceleration constant
H	Height
HV	Low Heating value of gas
HC	Hydrocarbon (expressed as equivalent methane)
h	Height of stack
ICBF	Incompletely burned fuel
K	Radiation heat flux
K_T	Tracer concentration ratio
L	Length
M	Molecular weight
m	Mass
$\dot{m}$	Mass flow rate
$\dot{m}^*$	Ratio of mass flow rates
N	Number of eddies

TABLE OF NOMENCLATURE (Cont'd)

Variable Symbol	Meaning
$\tilde{N}$	Number of moles
n	Number of atoms per molecule
O	Global efficiency based on oxygen consumption
P	Pressure
Q	Radiation intensity per unit volume of product
R	Gas constant
Re	Reynolds number
Ri	Richardson number
r	Radius or intermediate variable
S	Dimensionless coordinate
SR	Stirred reactor
T	Temperature
t	Time
U	Global efficiency
u	Velocity
V	Volume
$\dot{V}$	Volumetric flow rate
w	Vertical velocity (ref. Brzustowski)
X_L	Dimensionless downwind coordinate
x	Radial distance from centerline
Y	Mass fraction
z	Axial distance from nozzle

TABLE OF NOMENCLATURE (Cont'd)

GREEK SYMBOLS

Symbol	Meaning
α	Local combustion efficiency based on CO_2
α_E	Empirical entrainment coefficient
α_{st}	Empirical factor used to predict the amount of steam required to suppress soot
β	Burning rate parameter
γ	Entrainment coefficient
δ	Thickness of jet
η	Local combustion efficiency based on pollutants
Θ	Jet spreading angle
λ	Kolmogorov length scale
μ	Viscosity
ξ	Dimensionless streamline coordinate
ρ	Density
$\check{\rho}$	Mixing cup density
σ	Standard deviation
$\sigma_{\overline{X}}$	Standard error of $\overline{x}$
Φ	Stoichiometric coefficient
Ω	Intermittence factor-fraction of the time the flame is present at radial distance X

TABLE OF NOMENCLATURE (Cont'd)

SUBSCRIPTS

Subscript Symbol	Meaning
a	Air
ad	Adiabatic
C	Carbon
c	Centerline values
e	Eddy
F	Flame
f	Fuel
j	Jet
L	Flame length
o	Conditions at nozzle
p	Products
s	Sonic
st	Steam
unhc	Unburned hydrocarbon
w	Wind
∞	Ambient conditions
overbar	Ambient conditions
[ ]	Concentrations

1.0 SUMMARY

The U.S. Environmental Protection Agency has contracted with Energy and Environmental Research Corporation to conduct a research program which will result in the quantification of emissions from and efficiencies of industrial flares. The study is being conducted in four phases:

- I - Experimental Design
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This report provides the results of Phases I and II of the study.

The report summarizes the technical literature on the use of flares and reviews available emission estimates. Technical critiques of past flare efficiency studies are provided. Mathematical models of flame behavior are explored, and recommendations for flare flame models are made.

The parameters affecting flare efficiency are evaluated and a detailed experimental test plan is developed. The design of a flare test facility is provided, including details on the flare tips, fuel and steam supply, flow control and measurement, emissions sampling and analysis, and data acquisition and processing. A Quality Assurance/Quality Control Program is also described. Results of the testing program (Phases III and IV) will be provided in the project's final report to be issued at a later date.

1.1 Pollutant Emissions from Flares

A flare is a device which allows the economic safe disposal of waste gases by combusting them. The waste gases are injected into the open air through a tip which is designed to promote entrainment of the ambient air and provide a stable flame with a wide range of throughputs in high cross-winds. In order to reduce flame radiation at ground level, the flare tip must be elevated and its height will be dependent upon flame size (i.e., flare throughput). If the waste gas has too low a heating value to sustain a flame, auxiliary fuel may be added. Small flares may utilize fans to provide some air premixing before injection, but most large flares are natural draft with optional steam injection to promote fuel air mixing. Flares are used extensively to burn purged and waste products from refineries, excess production from oil wells, vented gas from blast furnaces, unused gas from coke ovens and gaseous wastes from the chemical industry.

An estimated 16M tons/yr of gas may be flared in the U.S. The amount is difficult to estimate because throughputs fluctuate widely with time and are seldom measured. The normal, time-average throughput is in the range of zero to 5 percent of design capacity, which is exceeded only during emergencies or upsets. The flared gases fall into three categories (Klett & Galeski, 1976):

- Low heating value gas produced in blast furnaces which account for 60 percent of the weight and 19 percent of the heating value of the estimated annual flared gases;
- Medium heating value gases produced in coke ovens and in the petrochemical industry;
- High heating value gases flared in refineries which account for 18 percent of the weight and 32 percent of the heating value of the estimated annual flared gases.

Pollutant emissions from flares result from a failure to completely combust the flared gases. The pollutant species are normally carbon monoxide, hydrocarbon and soot, and total emissions are assessed based upon an estimate of flare efficiency. The efficiency of combustion of a flare, which is a measure of its ability to destroy the flared gas, is difficult to measure, and consequently estimates of pollutant emission indices vary. Estimates of flare efficiencies vary widely, some are very high, in excess of 99 percent, whereas others range as low as 70 percent (T.A. - Luft 1974) leading to the conclusion that emission factors are unknown. If flares were 90 percent efficient, then emissions of carbon monoxide and hydrocarbons would be approximately 12 percent of those emitted by all stationary sources. More important are the contributions of flares as localized sources because of their concentration in refineries and steel plants where they could be among the most significant sources of pollutants if the efficiencies are relatively low.

It can only be concluded that pollutant emissions from elevated flares are unknown. This is due to a combination of uncertainties in the quantity of gases being flared and their composition together with the uncertainties in flare efficiency. Before a decision can be made whether pollutant emissions from flares are of concern, an accurate assessment of flare efficiency must be made. Theoretical estimates of flare efficiency cannot be made, emission measurements from operating flares are difficult and previous pilot scale studies are contradictory or incomplete. Thus, there is a need for a study to accurately assess flare efficiency as a function of:

- flared gas composition;
- throughput;
- flare design and operation (steam injection, etc.);
- ambient conditions;
- scale.

Data from this study can then be used to provide an accurate assessment of pollutant emissions from flares.

1.2 Deficiencies in Previous Flare Emission Studies

There have been relatively few investigations reported in the open literature concerned with pollutant emission or efficiency of flares.

Table 1-1 summarizes the most recent, known studies, each of which addressed one or more of the following topics:

- the emissions of incompletely burned material;
- the distance required to burn the flared gases;
- the impact of steam injection on pollutant emissions;
- the effect of ambient conditions on pollutant emissions.

Although these studies have made valuable contributions to the knowledge of flare performance, none allow an accurate determination of pollutant emissions nor do they provide adequate information on the effects of scale or flared gas composition.

A review of the previous studies indicates that data acquisition and manipulation are the common problems which prevent an accurate assessment of flare efficiency. These problems are discussed below in four main areas, namely:

TABLE 1-1. PREVIOUS FLARE EMISSION STUDIES

Investigator	Flare Tip Design	Flared Gas	Throughput M Btu/hr	Flare Efficiency %
Palmer (1972)	0.5" dia.	Ethylene	0.4 - 2.1	> 97.8
Lee & Whipple (1981)	Discrete Holes in 2" dia. cap.	Propane	0.3	96 - 100
Siegel (1980)	Commercial Design (27.6" dia. steam)	≈ 50% H_2 plus light hydrocarbons	49 - 178	97 - > 99
Howes et al (1981)	Commercial Design (6" dia. air assist)	Propane	44	91 - 100
	Commercial Design H.P. (3 tips @ 4" dia.)	Natural Gas	28 (per tip)	> 99

- Inability to close a material balance.
- Measurement of soot concentration.
- Difficulties caused by flare "intermittency".
- Lack of scaling methodology.

Closure of Material Balance

The global (overall) efficiency of a flare flame can be calculated if the inlet fuel composition and mass flux is known together with mass flux of all hydrogen and carbon containing species of flared material at some height above the flame where all reaction has ceased. There is more interest in that fraction of the fuel flux that becomes air polluting species rather than harmless CO_2 and H_2O. It is usual to concentrate on the carbon in the fuel because all of the ultimate air polluting species contain it (i.e., CO, H_xC_y, soot). If the carbon fraction of all product gas flux species is summed, the result should equal the carbon fraction of fuel mass flux. This is the usual mass balance concept and is an accounting check on the pollutant species measurements. It is easy to state but rather difficult to implement. Of the studies in Table 1-1, only Siegel attempted to close the mass balance. Generally he was only able to account for approximately half of the fuel carbon in the off-gas flux. Siegel stated that the largest errors were associated with the velocity measurements needed to determine the mass flux. Siegel circumvents the need for further mass balance by using "local burnout" efficiency, and showing that errors in the resulting global efficiency values are minor.

A material balance requires time averaged concentration, velocity and temperature measurements at some plane normal to the mean direction of flow. These measurements are made above the flame when total emissions are being assessed which requires an integration of the species flux across the total jet. The major errors which prevent adequate material balance closure are:

- Material escapes undetected, because at the flame extremities dilution lowers its concentration below the detectability limit of the analytical equipment;
- All the species are not measured;
- The time average velocity is difficult to measure in and near turbulent flames.

A tracer in the fuel can be used to aid in obtaining a mass balance by yielding a double check on the dilution factor in the product gases. However, the use of a tracer does not eliminate the need for velocity measurements in determination of mass flux. More details on tracers will be discussed in Section 7.7.2.

Measurement of Soot Concentration

Soot represents uncombusted fuel carbon which should be included in flare flame efficiency calculations. Siegel (1980) measured soot concentrations between 20 and 80 mg/m^3 in an intentionally smoking flame, estimating that at those dilution conditions this reduced flare efficiency by 3 to 4 percentage points. More recently, Howes, et al (1981) performed soot measurements in a smoking propane flame. Using a dilution factor obtained from the CO_2 concentration, the 18 mg/m^3 of soot measured represented a decrease in combustion efficiency of 0.4 percent. It should be noted that these local efficiencies are not equivalent to global efficiency, since they were samples collected at one sampling point.

Flare Intermittency

The term "intermittency" essentially means that at one fixed point above the flare, the flame is not present all of the time. Even in calm wind conditions, the turbulence induced by the combustion process causes the flame to undulate and appear unsteady. This usually causes corresponding fluctuations in measured quantitites at fixed points above the flame. Using sufficient sampling times provides one means of time averaging data to avoid this intermittency effect. As discussed in Sections 1 and 8, one objective of the proposed experimental plan is to determine sampling times so that the characteristics of the flame are measured, unmasked by intermittency.

Scaling Methodology

The studies listed in Table 1-1 did not provide a methodology whereby the data from these pilot scale or small, plant scale flares could be used to assess the emissions from the total population of flares. A methodology is required which will allow data to be obtained economically at pilot scale and used to determine performance of full scale systems. The current state-of-the-art of turbulent flame structure precludes the use of predictive models. Thus the experimental plan must provide data which will allow the effects of scale to be determined and in conjuction with developing theories of turbulent flame structure will allow extrapolation to full scale.

1.3 Technical Approach

As will be shown in the Background Section, current information on flare combustion is fragmentary and inconclusive. This program attempts to answer these questions:

- What are the combustion efficiencies of small flare flames?
- How are these efficiencies influenced by operational parameters, flare design, fuel composition and scale?
- What are the mechanisms of these influences?
- How can the efficiencies of large industrial flares be estimated?

A research program with emphasis in experimental measurements on a pilot scale flare is the most cost-effective way to approach these questions. It must fulfill these requirements:

- Representativeness - The hardware and operational conditions must relate to full scale practice.
- Data Accuracy - The measurement methods must be developed and verified satisfactorily to eliminate the uncertainties that plagued previous experiments.
- Basic Understanding - Experiments must be designed to bring understanding on the underlying controlling processes that take place in flare flames.
- Extrapolation - Information must be generated to extend the applicability of the small scale data to full scale flares.

The design of valid experiments on flares must consider the fact that flare flames are different from other combustion processes, such as enclosed boiler flames, in that they are buoyancy dominated, are affected by ambient air movements, and lose heat to a much colder environment. It is commonly accepted that if sufficient air is mixed with the fuel and if the resultant mixture is kept above the reaction temperature, combustion will go to near 100% completion. However, these two conditions are not necessarily true in flare combustion systems, particularly for the fuel eddies that are separated from the main flame body. Because of the geometry of the eddies, they tend to be quenched at a higher rate than the main flame body and hence are more likely to be extinguished before all the fuel is burned.

The presence of oxygen next to the fuel is essential for continuation of combustion. In a flare flame, air may be entrained into the fuel jet by natural convection and assisted by forced convection through air- or steam-assist. The effectiveness of these mixing processes directly affects the combustion reaction. If the mixing is not completed before the burning fuel elements are quenched below the reaction temperature, the flame will be extinguished. Therefore, the research program must develop the basic understanding of the mixing and eddy behavior of flare flames. This may be aided by modeling which will be discussed in more detail later on in this report.

The main emphasis of the research program will be the measurements and characterization of emissions and flame structures. It will include these considerations:

- Four flare sizes (1½, 3, 6 and 12 inches in diameter) will be linearly scaled replicas of each other and will include features of commercial flares.
- Detailed measurements will be made throughout and beyond the visible flame envelope to determine profiles of temperature and species concentration.
- Tracers will be injected and measured to assess air entrainment.
- Photography will record flame structures .

The experiments will start with the smaller flares to develop and verify the measurement methods. Once the baseline flare behavior is defined, the effects of operational parameters and scale will be studied.

The experimental test program can be logically divided into four tasks.

The Task 1 objective is generation of a data base of gross flame parameters as a function of the complete range of all input parameters. This will be a rapid screening process on all flare sizes to assess the major effects of fuel rate, wind level, steam rate, and gas composition. The output measurements will be limited to visual and photographic observations of flame length, form and structure, and sooting tendency. Video recordings can also supplement the photographic technique. The utility of this task lies in its identification of those regimes of the original test plan that need greater emphasis in the succeeding tasks.

Task 2 will be concerned with development and verification of all measurement techniques. This can most effectively be done using the smaller flare sizes. The measurements will consist of species concentration measurements in and near the flame, including a tracer. Development of an integrating hood will be included. A major objective of this task is verification of an adequate carbon mass balance to provide confidence in the succeeding task.

Task 3 will be concerned with the detailed measurements according to the test plan as revised by Task 1. The major effort will be on the smaller sizes, with the knowledge gained indicating the most important test conditions to be used for the limited number of large size tests.

Task 4 is a general category related to continuous evaluation of test data, development of modeling and scaling parameters and documentation. A more detailed breakdown of these tasks is found in Section 4.

1.4 Report Organization

The report describes the background related to flare design, characteristics and emissions in Section 2. Sections 3 and 4 discuss the need for futher work and a technical approach to carry this work out. Section 5 gives a review of the potential test facilities which may be considered for the experiments. The design objectives, a facility description and the measurement techniques to be used in assessing flare characteristics are described in Sections 6 and 7. Section 8 discusses data analysis and application of the information generated in the experimental program.

2.0 BACKGROUND

The primary use of flares by industry is the safe venting and combustion of process gases during emergency or "upset" conditions. They are also available to dispose of much lower flowrates of waste gas that occur during normal process operation. It is this latter condition that prevails most of the time and is thus of major importance in determination of flare efficiency. Industrial flares encompass a wide variety of conditions; both in terms of the type of installation and operating conditions. Important factors are gas composition, heating value and percent dilution by inert gases, flowrate, ambient conditions and combustion assist features, such as steam or forced draft air. These depend on the type of plant and its location such that flare designs tend to be site specific. Consequently, there is a wealth of hard engineering experience with respect to flare design and adaptation to different conditions, but due to the varied nature of the flaring process, there is a lack of comprehensive information in the open literature with regard to specific operational details as they affect the waste gas combustion process. There is only meager and often contradictory information published on the potentially harmful materials issuing from industrial flares; thus there exists an information gap that must be closed in order to assess the environmental impact of flare systems.

Within this framework, the objective of this present program is to define an experimental plan which will both improve the understanding of flare combustion, and provide a means of estimating emissions from flares of various sizes and characteristics. There is a great deal of background information which is relevant to this task, and the purpose of this section is to review the important available literature in order to define the scope of the required experimental program. Of particular interest is information concerning flare use and the range of gas compositions encountered in the different industries, flare designs and the range of operating conditions, and experimental data and methods available for the modeling and scaling of flare type combustion.

In recent years, a number of surveys of flare use have been carried out, both in the United States and abroad, in an attempt to define the significance of flare emissions. Results from such studies provide a basis for the estimation of total gas quantities flared, the range of gas compositions encountered, and, by inference, possible emission factors for the different industries. Information is also available concerning flare types and design methods, although the nature of the flare combustion process, and the lack of appropriate measurement methods, has precluded the kind of detailed study that would permit a definition of combustion efficiencies or allow quantification of the effect of different flare design parameters. A number of small and pilot scale studies have, however, been carried out, and these are reviewed to provide insight into the relevance of small scale experiments and the possibilities for data extrapolation. Much of the available data shows, however, that our knowledge of basic combustion phenomena is lacking in certain areas, and that direct transfer of experimental data from small to full scale is usually not possible. To this end, a simple mathematical modeling approach is required to provide direction for the design of small scale experiments and a means of defining scaling criteria by which the data can be extrapolated. Available modeling approaches and basic information concerning the characteristics of large turbulent diffusion flames are reviewed in this light.

2.1 Use of Industrial Flares

Much of the information on use, design, and operation of flares has been reviewed by Klett and Galeski (1976). More recently the German Society for Petroleum Sciences and Coal Chemistry, DGMK, (Program 135-01) analyzed the results of a questionnaire sent to 31 German refineries. Unpublished results from a questionnaire sent out to California refiners by the California Air Resources Board (Metzger and Vincent, 1980) has also been made available. Most of the information which follows is based on these studies.

Flares are designed for the maximum anticipated gas release caused by process upset or emergency shutdown. These conditions occur infrequently and are of relatively short duration. A lower level continuous or semi-continuous release is caused by leaks in equipment, necessary venting of a process, and purging of gases during start up and shutdown. These flows, while of much reduced magnitude compared to emergency use, occur most of the time. Thus, a flare must be a very flexible device, capable of high throughput, and sustained operation at a high turn down ratio. For instance, an instantaneous flow rate of 100 MSCF/hr may be demanded while sustained normal operation occurs at 1/1000 of this value.

This section reviews the industries in which flares are used, characterizes the gases flared, and estimates the amount of gas flared in these industries. Unfortunately, the use of flares is largely uncontrolled and, hence, the flow rates of gases are infrequently monitored. Flow rates are only occasionally measured so that the amount of steam required to suppress smoking can be regulated. Rough estimates have been made of the amount of gas flared in four major industrial operations: oil refining, blast furnaces, coke ovens, and ethylene manufacturing for 1974. Here we extrapolate this estimate to 1980 and estimate the amount of gas flared in petroleum production and the chemical industry.

2.1.1 Petroleum Refining

The petroleum industry flares large quantities of gas from refinery operations and production wells.

Table 2-1 has been constructed from the data of California Air Resources Board Survey. Although the number of initial questionnaires sent out is unknown, the 63 flares referenced by the 21 respondents show very similar characteristics. Although "emergency" is the primary use, continuous use is also assumed. Steam is the most universal means of smoke suppression. None of the flares are equipped to measure flow rate of the flared gas, so annual amounts are only estimates. The composition and heating value vary widely.

These results are similar to the results from the German refinery survey (DGMK, 1981) wherein thirty-one West German refineries responded. Figure 2-1 shows the flare gas density variation from one of these refineries during the period in 1978 of Siegel's research there. The flowrate is that of Siegel's side stream and not the main flare.

Generally, the gas flared in refineries is not measured and thus is difficult to estimate. However, gases flared in refineries contribute significantly to the total amount of gas flared in the United States. Therefore, the amount of gas flared in petroleum refining must be estimated, if the total emissions of incompletely burned fuel is to be estimated.

In 1974, a survey (Table 2-2) of 11 of the 288 refineries in the United States showed that from 0.039 to 2.8 percent of the refinery throughput was flared. The average amount flared excluding the highest number was about 0.2

TABLE 2-1. SURVEY OF CALIFORNIA OIL REFINERY FLARES (CALIFORNIA AIR RESOURCE BOARD, 1980)

Refinery	Flare Type	Flare Diameter (in)	Smoke Suppression	Service	Annual Flowrate scf/yr	Fuel	Steam/Fuel
1	Elevated	30	Steam	Emergency	---	---	~0.35
1	Elevated	24	Steam	Emergency	---	---	~0.35
1	Elevated	24	Steam	Emergency	---	---	~0.35
2	Elevated	---	Steam	Continuous	---	---	---
3	Elevated	30	Steam	Emergency	---	H_2, CO, N_2, C_1-C_3	---
3	Elevated	30	Steam	Emergency	---	---	---
3	Elevated	8	Steam	Emergency	---	---	---
4	Ground	---	Steam	Emergency	---	---	0.40
4	Elevated	30	Steam	Emergency	---	---	0.38
4	Elevated	8	Steam	Emergency	---	C_1, C_4, S	0.30
4	Elevated	10	Steam	Emergency	---	LPG	---
5	Ground	---	Steam	Emergency	180M	---	---
5	Elevated	---	Steam	Emergency	---	---	---
5	Elevated	16	Steam	Emergency	---	---	---
5	Elevated	20	Steam	Emergency	---	---	---
5	Elevated	10	Steam	Emergency	---	---	---
6	Elevated	30	Steam	Emergency	36M	---	---
7	Ground	---	Venturi	Emergency	---	---	---
8	Elevated	8	Steam	Con't & Emer.	---	---	~0.5
9	Elevated	8	Steam	Emergency	50M	H_2, C_1-C_6, H_2O	1.7
9	Elevated	12	Steam	Emergency	3.5M	H_2, C_1-C_6, H_2O	1.7
10	Elevated	---	Steam	Emergency	0.9M	---	0.5
11	Elevated	36	Steam	Emergency	----	---	~0.3
11	Elevated	36	Steam	Emergency	---	---	~0.3
11	Elevated	36	Steam	Emergency	---	---	~0.3
11	Elevated	10	Steam	Emergency	---	---	~0.3
12	Elevated	18	Steam	Emergency	547M	HC, H_2S, RSR	0.3 ->1.
13	Elevated	31	Steam	Emergency	---	HC, H_2S, RSR	0.33
14	Elevated	6	Steam	Con't & Emer.	3.9M	C_1-C_5, H_2	0.43
15	Elevated	48	Steam	Emergency	111	---	0.3-0.4
15	Elevated	48	Steam	Emergency	283	---	0.3-0.4
15	---	30	Forced Draft	Emergency	1.2	---	---
15	Elevated	16	Steam	Emergency	27.6	---	0.2-0.35
16	Elevated	36	Steam	Emergency	---	C_1,C_2, H_2, N_2, H_2, O_2, CO_2	~0-2.
16	Elevated	36	Steam	Emergency	---	C_1,C_2, H_2, N_2, H_2, O_2, CO_2	~0-2.
16	Ground	---	Steam	Emergency	---	C_1,C_2, H_2, N_2, H_2, O_2, CO_2	~0-2.
16	Elevated	36	Steam	Emergency	---	C_1,C_2, H_2, N_2, H_2, O_2, CO_2	~0-2.
16	Elevated	36	Steam	Emergency	---	C_1,C_2, H_2, N_2, H_2, O_2, CO_2	~0-2.

TABLE 2-1. SURVEY OF CALIFORNIA OIL REFINERY FLARES (CONTINUED)
(CALIFORNIA AIR RESOURCE BOARD, 1980)

Refinery	Flare Type	Flare Diameter (in)	Smoke Suppression	Service	Annual Flowrate scf/yr	Fuel	Steam/Fuel
16	Elevated	42	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2, CO_2	~0-2.
16	Elevated	42	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
16	Elevated	48	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
16	Elevated	---	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
16	Elevated	70	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
16	Elevated	---	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
16	Elevated	---	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
17	Ground	---	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
17	Elevated	42/100	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
17	Elevated	36	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
17	Elevated	---	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
17	Elevated	48/72	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
17	Elevated	12	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
17	Elevated	12	Steam	Emergency	---	C_1,C_2, H_2, N_2,H_2, O_2,CO_2	~0-2.
18	Elevated	---	Steam	Emergency	10,740	C_1-C_5,NH_3,CO_2 H_2S	~0.3
18	Elevated	---	Steam	Emergency			0.3
19	Elevated	42	Steam	Emergency	---	---	~0.3
19	Elevated	36	Steam	Emergency	---	---	~0.3
19	Ground	---	---	Emergency	---	---	0
20	Ground	---	Steam	Emergency	---		---
20	Elevated	---	Steam	Emergency	---		---
20	Elevated	---	Steam	Emergency	---		---
20	Elevated	---	Steam	Emergency	---		---
20	Elevated	---	Venturi	Emergency	---		---
21	Ground	---	Self-Inspiration	Emergency	0.25M	C_1-C_3	0

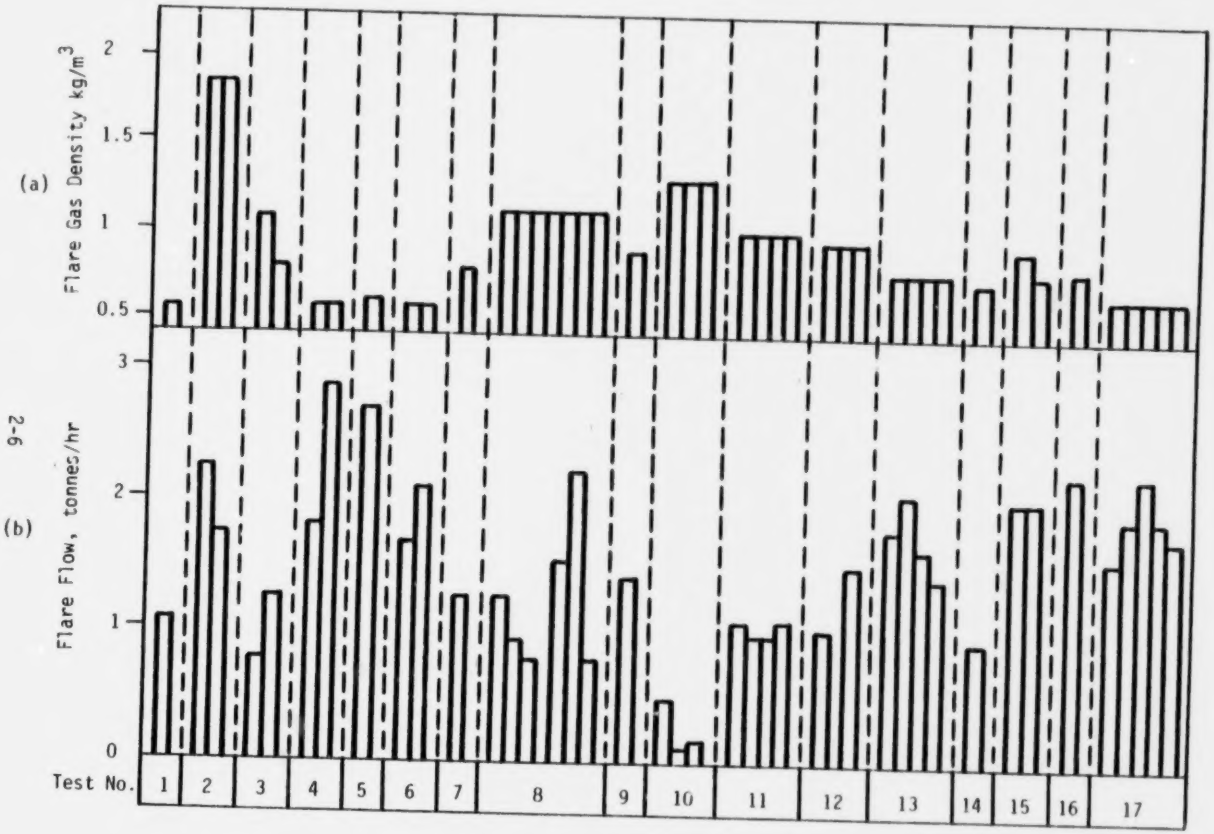


Figure 2-1. (a) Variation in gas density flared from a German Refinery; (b) Actual flow rate of test flare used by Siegel (1980).

TABLE 2-2. GAS FLARED IN U.S. REFINERIES
(KLETT AND GALESKI, 1976)

Refinery	Refinery Throughput bbl/cd	% Flared	Composition (%)								Total Hydro-carbon lb/cd	Composition			
			C_1	C_2	C_3	C_4	C_5	Aromatic	Olefins	Parafins		H_2	H_2S	NH_3	Other
1	54,437	0.170	0	1.2	1.8	2.4	0	0	0	5.4	5.4	0	9.4	0	85.1
2	167,658	0.554	49.4	14.5	12.9	9.3	11.1	0	10.3	87.0	97.3	1.9	0.8	0	0
3	213,000	0.143	2.3	5.1	70.5	30.5	40.0	11.5	29.5	57.4	98.4	1.6	0.0	0	0
4	73,700	0.145	47.9	14.9	14.2	12.2	8.9	0	10.3	87.7	98.1	0.6	0.9	0	0
5	106,064	0.059	11.1	26.0	1.8	2.8	2.5	0	12.7	31.4	44.2	1.0	43.8	1.3	9.8
6	255,000	0.039	7.8	32.4	29.2	14.3	6.8	1.2	17.7	75.0	93.8	3.2	2.9	0	0
7	239,400	0.056	8.5	8.4	34.4	41.7	4.5	0	9.7	87.7	97.5	1.4	1.1	0	0
8	369,500	0.210	7.3	9.1	53.6	5.3	8.8	0	10.2	75.1	85.3	0.4	2.1	0	12.2
9	112,652	0.604	20.9	17.8	34.9	11.5	8.6	0	19.7	74.0	93.7	1.6	1.3	0	3.3
10	162,908	0.142	22.9	32.1	18.1	7.2	8.9	0	11.8	77.4	89.1	4.6	6.3	0	0
11	145,060	0.189	24.2	13.2	67.3	7.1	4.2	0	0	94.3	94.3	0.4	0.5	0	4.7
Total	1,899,419	0.19	23.3	14.4	31.6	11.4	11.0	1.0	12.9	76.3	90.2	1.5	2.4	0	5.8
12	306,590	2.78	8.3	6.5	48.4	33.6	3.1	0	0	100.0	100.0	0	0	0	0

percent. This number is the same as that estimated by Siegel (1980) for German refineries. About 12.3 x 10^6 BBL/cd (cd = calendar day) of petroleum was refined in 1974. Therefore, petroleum refineries flared approximately 7.4 x 10^6 lb/cd of gas based on barrels refined. The figures for 1980 are 18 x 10^6 BBL/cd refined and 10.8 x 10^6 lb/cd of gas flared.

The composition of gas flared in refineries varies widely, both within a refinery (Figure 2-1 and Figure 2-2 and Table 2-3) and between refineries. (Table 2-1 and 2-2). The amount of gas flared in a German refinery varied by a factor of 22, the density by a factor of 3.4, and the composition of some species by a factor of 5. However, most of the refinery gases flares are light paraffinic hydrocarbons with large amounts of C_3 and C_4 compounds. An average composition for a refinery gas is shown in Table 2-4.

2.1.2 Petroleum Production

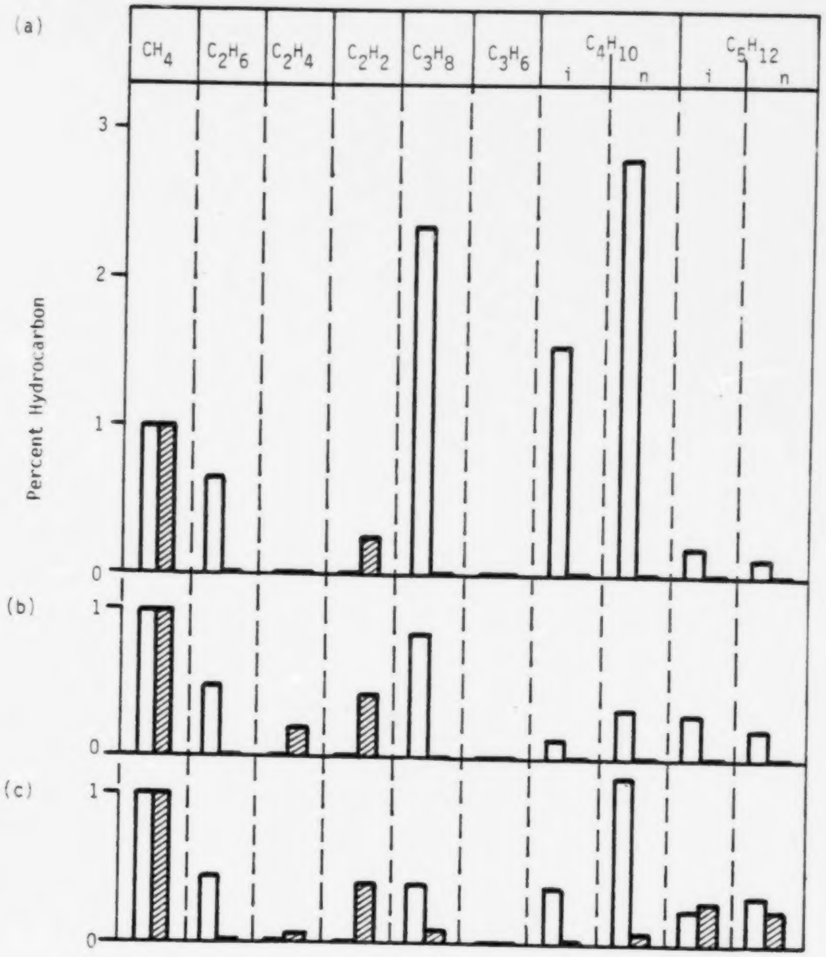
Gas flared during production of petroleum also contributes to the total amount of gas flared in the United States. In the past, large amounts of low molecular weight gases have been flared from oil producing wells. This practice has been reduced recently, since the gas product is now valuable and much of it can be sold.

The amount of gas flared in petroleum production has not been previously estimated, and it is difficult to make such an estimate. In one report approximately 0.7 percent of the oil production was flared (Minkkinen, 1981). Assuming a ratio of 0.5 percent gas flared to all petroleum production in the United States, the 10 MBBL/cd produced in the United States in 1980 resulted in the flaring of approximately 3 M tons/yr of gases from oil production.

The composition of gases flared during production of petroleum is the same as natural gas. These gases are mostly methane with small quantities of other light hydrocarbon gases and inert gases (Table 2-5).

2.1.3 Blast Furnaces

Another major use of flares is to dispose of waste gas from the blast furnaces used in the iron and steel industries. As in refineries, blast furnace gases are flared intermittently to control process pressures. Gases flared from blast furnaces account for approximately 60 percent of the weight



		a	b	c
$\dot{m}_{Gas}$	(t/h)	2.2	0.94	0.75
ρ^{0}_{Gas}	(kg/m^3)	1.86	1.0	1.1
$\frac{\dot{m}\ steam}{\dot{m}\ Gas}$	(kg/kg)	0.37	0	0.24

▯ flare gas

▨ off-gas

Figure 2-2. Volume ratios of hydrocarbons in the flare and off-gas for three tests on a flare at a German refinery (Siegel, 1980).

TABLE 2-3. FLARE GAS COMPOSITION FROM A GERMAN REFINERY (SIEGEL, 1980)

Gas	01.010 -.045	02.001 -.086	03.040 -.094	06.010 -.174	07.055 -.077	08.001 -.132	08.133 -.172	11.011 -.105	12.030 -.034	13.001 -.020	14.017 -.031	15 RUN	16.001 -.089	17.001 -.051
H_2	69.3[a]	17.8	56.1	63.3	63.1	55.7	50.4	50.6	45.4	63.0	63.4	53.4	58.8	64.1
H_2S	1.3	0.4	1.5	bdl[b]	bdl	bdl	bdl	0.2	bdl	bdl	bdl	0.1	bdl	0.2
CH_4	8.9	8.9	11.6	12.3	10.6	11.9	12.6	13.8	10.3	13.9	12.3	11.5	6.7	7.4
C_2H_6	7.2	5.8	9.0	10.2	6.0	5.8	6.8	6.8	4.8	6.5	4.8	7.3	5.0	5.3
C_2H_4	0.04	0.06	0.02	0.01	0.01	0.02	0.02	0.01	bdl	0.02	bdl	bdl	bdl	bdl
C_2H_2	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bld	bdl	bdl	bdl	bdl	bdl
C_3H_8	5.5	21.0	12.8	6.9	4.6	4.5	18.3	11.8	4.2	3.5	7.6	6.0	4.3	4.2
C_3H_6	0.06	0.06	0.1	0.04	0.1	0.2	0.2	0.04	bdl	0.1	bdl	bdl	bdl	bdl
i-C_4H_{10}	1.0	14.1	2.0	0.9	1.0	1.0	0.4	2.2	4.1	1.0	2.0	4.7	3.1	1.7
n-C_4H_{10}	1.4	24.9	2.7	2.3	6.7	0.2	0.9	5.0	12.1	2.0	4.0	8.5	6.8	2.8
i-C_4H_8	0.03	0.1	0.06	bdl	bdl	0.2	0.1	bdl	bdl	bdl	bdl	bdl	bdl	bdl
n-C_5H_{12}	1.9	1.9	2.0	2.4	3.0	5.7	3.3	4.7	2.8	5.1	3.9	6.3	1.8	2.2
i-C_5H_{12}	1.2	1.2	1.5	1.2	3.2	8.1	4.3	3.2	3.8	3.6	1.4	1.1	0.6	1.1
C_5H_{10}	bdl	0.6	0.5	0.2	1.8	5.6	2.6	0.8	3.5	1.5	0.3	1.4	0.3	bdl
C_6H_{14}	bdl	0.1	bdl	bdl	bdl	1.1	0.3	bdl	bdl	bdl	bdl	bdl	bdl	bdl
C_6H_6	bdl	1.0	bdl	bdl	bdl	0.1	0.3	bdl	bdl	bdl	bdl	bdl	bdl	bdl
C_6H_5-CH_3	bdl	0.2	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
C_6H_5-C_2H_5	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	7.5	bdl	bdl	bdl	bdl	bdl
N_2	2.2	1.8	bdl	bdl	bdl	bdl	bdl	0.6	1.7	bdl	bdl	bdl	11.4	11.2
H_2O	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	1.8	bdl

a - The largest and second largest component are underlined. b - Below detection limits

TABLE 2-4. CHARACTERISTICS OF GASES FLARED IN THE UNITED STATES

	Flared Gas MTon/yr	Heating Value Btu/ft^3	CH_4	Parafins	Olefins	Aromatic	H_2	CO	Inerts H_2O, N_2 CO_2
Refineries	2.1	1750	-	76.3	12.9	1.0	1.5	2.5	5.8
Petroleum Production	3.0	1000	75-95	80-95	0.0	0.0	0.0	0.0	0-17
Blast Furnace	9.6	90	Balance	-	-	-	Balance	23.8	76
Coke Ovens	0.2	700		30	2		3.5	7.1	59.2
Chemical Industry*	1.2	1800		9	0.0		2	3	5

* Estimated in Section 2.2.

TABLE 2-5. COMPOSITION OF GASES FLARED DURING PETROLEUM PRODUCTION

Compound	Reference			
	Oenbring & Sitterman (1980)	Minkkinen (1981)	Dryden (1975)	Perry (1973)
	LA Flare	Flares	USA Natural Gas	USA Natural Gas
CH_4	95.71	---	70-95	73-95
C_2H_6	2.94	---	3-18	2.5-8
C_3H_8	0.16	---	5	0.6-3
iC_4H_{10}	0.02	4.0		0.1-0.7
nC_4H_{10}	0.01	---		
CO_2	0.86	---	0.1-7	0-1
N_2	0.30	---	1-14	0.1-17
H_2S	---	---	---	---
MW	16.8	23.3	---	---
Heating Value Btu/ft^3	923		1050	950-1100

and 19 percent of the Btu content of all gases flared.

The flowrate of combustible gas flared divided by blast furnace throughput capacity serves as an indicator for this industry. In Table 2-6, it is seen that this figure varies from 0.07 percent to 43.2 percent. On the average 6.7 percent of blast furnace capacity was flared in 1974 when the production of blast furnaces was 145.5 x 10^6 tons/yr. Since steel production has changed little from 1974 to 1980, based on a production of 145.5 x 10^6 ton/yr, 52.6 M lb/cd of blast furnace gas is assumed to have flared in 1980.

The gases from different blast furnaces vary somewhat in composition (Table 2-6). However, about 76 percent of the gas is inert compounds (such as N_2 and CO_2) and carbon monoxide accounts for 99 percent of the combustible gases. The balance is hydrogen and methane. The typical heating value of blast furnace gas is around 90 Btu/ft^3.

2.1.4 Coke Ovens

Large amounts of gas are released when coke ovens are discharged. Much of this gas is burned in the steel works, but some of it must be flared.

Estimates in 1974 indicated that approximately 0.4 percent of the production of coke ovens is flared as combustible gases (Table 2-7). The production of coke ovens in this period was 55 x 10^6 tons and the amount of combustible gas flared was 1.1 x 10^6 lb/cd. The amount of gas flared in 1980 should be approximately equal to that flared in 1974 since steel production has changed little in the intervening period.

Table 2-7 shows that a representative average composition is 30 percent hydrocarbons, 60 percent inerts, and the remainder hydrogen and CO. The heating value would be about 700 Btu/ft^3.

2.1.5 Chemical Process Industry

The chemical process industry is the fifth major user of flares. The amount and composition of the gases flared in the chemical industry is more highly variable than the other industries discussed. This is due to the wide range of processes and products in the chemical industry.

A 1974 survey (Klett and Galeski, 1976) showed large variations in the amount of gas flared from different chemical industries (Table 2-8). A pre-

TABLE 2-6. SURVEY OF GASES FLARED FROM BLAST FURNACES (KLETT & GALESKI, 1976)

Plant No.	Capacity in Mlb/cd	Combustibles Flared in Mlb/cd	Composition (Weight %)				% Combustibles Flared of Capacity
			CO	H_2	CH_4	N_2+CO_2	
1	13.4	0.335	24.1	0.1	0	75.8	2.5 %
2	4.4	0.003	25.0	0	0	75.0	0.07
3	5.6	0.941	30.9	0.2	---	68.9	16.8
4	7.2	0.866	17.8	0.1	---	82.1	12.0
5	1.8	0.198	41.6	0.2	---	58.2	11.0
6	8.6	0.016	27.1	---	---	72.9	0.19
7	5.0	0.466	21.8	0.3	---	77.9	9.32
8	13.8	1.306	23.1	0.3	---	76.6	9.46
9	1.0	0.093	22.2	0.4	---	77.4	9.30
10	10.4	3.279	22.2	0.3	---	77.5	31.5
11	5.2	2.244	27.8	0.2	0.1	71.9	43.2
12	5.0	0.241	26.8	0.1	---	73.1	4.82
13	4.0	0.351	23.0	0.2	---	76.8	8.78
14	7.8	0.256	22.6	0.2	---	77.2	3.28
15	6.4	0.209	22.6	0.2	---	77.2	3.27
16	15.2	0.171	58.6	---	---	41.4	1.13
17	32.0	0.165	24.9	0.1	---	75.0	0.52
18	6.8	0.232	24.5	0.2	---	75.3	3.41
19	23.4	0.691	23.4	0.2	0.4	76.0	2.95
20	11.0	0.181	21.2	0.2	0.1	78.5	1.65
21	5.4	0.217	21.7	---	---	78.3	4.02
22	11.8	0.392	64.7	---	---	35.3	3.32
23	1.6	0.177	25.5	0.1	---	74.4	11.1
24	8.0	0.248	25.6	0.2	---	74.2	3.10
25	12.0	0.190	20.8	0.2	---	79.0	1.58
26	13.2	0.755	26.0	0.1	---	73.9	5.70
27	11.6	0.557	26.0	0.1	---	73.9	4.80
28	26.0	1.674	20.2	0.2	0.3	79.3	6.40
29	5.2	0.680	20.8	0.2	---	79.0	13.1
30	1.2	0.066	20.8	0.2	---	79.0	5.50
31	7.0	0.922	21.2	0.2	---	78.6	13.2
32	2.4	0.890	23.6	0.2	---	76.2	37.1
33	2.2	0.043	37.1	10.5	---	52.4	1.95
34	5.0	0.249	25.8	0.1	---	74.1	4.98
35	5.0	1.125	23.8	0.4	---	75.8	22.5
Total	305.6	20.431	23.39	0.22	0.05	76.34	6.69

TABLE 2-7. SURVEY OF GASES FLARED FROM COKE OVENS (KLETT & GALESKI, 1976)

Plant No.	Process in 1000 lb/cd	Composition					Total Combustible lb/cd	% Product Flared
		Hydro-Carbons %	H_2	CO	H_2S	N_2, CO_2 H_2O		
1	1,000	13.6	0.4	4.1	0.2	81.7	84,500	8.45
2	900	57.1	8.6	17.1	---	17.1	2,900	0.30
3	4,340	69.2	7.7	7.7	---	15.4	1,100	0.03
4	2,680	52.9	5.9	17.6	---	23.5	1,300	0.05
5	7,880	47.7	13.5	24.3	---	14.4	9,600	0.12
6	4,020	73.5	5.2	4.8	0.6	15.9	24,500	0.61
7	820	53.6	10.3	14.4	1.1	20.6	15,200	1.85
8	4,680	56.5	13.0	18.5	---	12.0	8,100	0.17
9	5,660	56.1	8.8	5.9	---	29.2	89,300	1.58
10	3,820	54.4	8.8	12.3	---	24.6	4,300	0.11
11	520	53.9	10.8	14.7	---	20.6	8,000	1.54
12	1,020	66.7	11.1	11.1	---	11.1	800	0.08
13	3,140	66.7	8.3	16.7	---	8.3	1,100	0.04
14	9,500	45.8	8.3	16.7	---	29.2	1,700	0.02
15	4,960	48.1	1.7	26.1	1.6	22.6	13,400	0.27
16	5,600	45.1	8.3	24.3	1.5	20.8	11,400	0.20
17	5,000	46.7	6.7	20.0	---	26.7	1,100	0.02
18	2,000	77.9	10.4	11.7	---	---	15,400	0.77
19	10,140	45.9	8.1	16.2	---	29.7	2,600	0.03
20	5,020	45.5	8.3	14.5	1.4	30.3	10,100	0.20
Total	86,700	30.2	3.5	6.9	0.3	59.2	306,400	0.35

TABLE 2-8. SURVEY OF GASES FLARED IN THE CHEMICAL INDUSTRY (KLETT & GALESKI, 1976)

Process	Capacity Mlb/yr	--------------Composition--------------					lb/cd Combustibles Flared	% of Combustible Capacity Flared
		Hydro-carbon	CO	H_2	N_2,H_2O CO_2	Other		
Ethylene	964	100.0	0	0	0	0	10,000	0.39
Ethylene	630	89.3	2.2	3.34	5.16	---	47,420	2.75
Ethylene	500	89.69	---	---	3.6	6.7	18,700	1.37
Ethylene	750	100.0	---	---	---	---	10,000	0.49
Ethylene	830	97.77	---	2.23	---	---	26,900	1.18
Ethylene	775	100.0	---	---	---	---	48,000	2.26
Acetylene	325	98.5	---	---	---	---	1,726	0.19
Aromatics	750	100.0	---	---	---	---	7,900	0.38
Petrochemicals	2,000	100.0	---	---	---	---	96,000	1.75
Petrochemicals	660	---	---	---	---	---	300	0.02
Polypropylene	260	73.4	---	---	26.6	---	55,200	7.75
Polypropylene	110	100.0	---	---	---	---	2,500	0.83
Butyl Rubber	200	100.0	---	---	---	---	36,000	6.57
Acetic Acid	110	100.0	---	---	---	---	8,700	2.89
Acetic Acid	110	10.0	25.0	50.1	15.0	---	67,200	22.30
Acetic Anbydride	160	35.9	45.3	---	18.75	---	15,600	3.56
Acetic Anbydride	140	59.9	26.0	0.26	13.86	---	100,700	26.25
Adipic Acid	380	---	---	---	---	100.0	---	---
Acrylonitrile	365	---	---	---	100.0	---	16	0.0016
Acrylonitrile	350	---	---	---	100.0	---	276	0.03
Ammonia	550	75.0	---	24.95	---	---	54,700	3.59
Ammonia	660	---	---	---	---	100.0	192	0.01
Ammonia	800	---	---	---	---	100.0	4,800	0.22
Alcohols	215	100.0	---	---	---	---	16,300	2.77
Carbon Black	244	0.77	6.48	0.62	92.0	0.139	37,500	5.61
Phosphorus	9	0.18	96.84	0.35	2.22	---	10,400	42.18
C_2S and S Recovery	73	81.1	---	---	---	18.9	444	0.22
NaHS	37	---	---	---	---	100.0	10	0.01
Aldicarb	53	86.1	---	---	---	14.67	3,600	2.48
CO for Phosgene	70	100.0	---	---	---	---	1,440	0.75
Oil Additive	342	100.0	---	---	---	---	10,900	1.16
Ethylene Loading^a	10^5 lb/hr	100.0	---	---	---	---	12,000	0.50
Ethylene Storage	.263	100.0	---	---	---	---	2	0.28
Butadine Storage	.536	90.9	---	---	---	---	1,100	74.9
Ammonia Storage	40	---	---	---	---	100.0	950	0.87
HCN Storage	.200	---	---	---	---	100.0	480	87.6
Tank Car Loading	---	90.0	---	---	10.0	---	1,080	---
Agodrin	12	100.0	---	---	---	---	96	0.29
Nudrin	6	46.9	---	---	21.9	31.25	32	0.19
Nudrin	6	---	---	---	75.0	25.0	6	0.04
Total (except a)	13,487	---	---	---	---	---	696,724	1.89

vious estimate has been made of the amount of material flared in ethylene production for 1974 (0.87 x 10^6 lb/cd), but no estimates have been made for the entire chemical industry and such estimates are difficult to make because of the wide variation in the amount of gas flared. However, if 2 percent of the production of petrochemicals was flared and the production of petrochemicals was 120 x 10^9 lb/hr in 1980, then 6.6 x 10^6 lb/cd of gas was flared from the petrochemical industry. This number is an order of magnitude estimate only.

The composition of the gases flared in the chemical industry varies primarily with the product produced (Table 2-8). However, most of the gases flared are composed largely of hydrocarbons. The heating value would vary according to the specific process involved.

2.1.6 Summary of Use of Industrial Flares

Flares are the only safe and economical way of disposing of sudden releases of large amounts of gas. Flares are used extensively to burn purged and waste products from refineries, excess gas production from oil wells, vented gas from blast furnaces, unused gas from coke ovens and waste and purge products from the chemical industry.

The amounts of gases flared in the industries is difficult to estimate because flows of flare gas are highly intermittent and usually not measured. Estimates made in previous sections show that 16 M tons/yr of gas may be flared in the U.S. Table 2-9 shows that blast furnace gas accounts for 60 percent by weight and 19 percent by heating value of these gases. Gases flared from petroleum production account for 18 percent by weight and 32 percent by heating value of flared gases. Most of the gas on the basis of weight or heating value is either blast furnace gas or refinery gas.

The compositions of gases flared in the United States are of two types (Table 2-4). The gases flared from refineries, petroleum production, and the chemical industry, and, to some extent, those flared from coke ovens are composed largely of low molecular weight hydrocarbons and have high heating values. Those flared from blast furnaces are largely of inert species and carbon monoxide and have a low heating value.

TABLE 2-9. ESTIMATE OF THE AMOUNT OF GAS FLARED IN THE U.S. IN 1980

Industry	Production 10^6 Tons/yr	Percent Flared	Amount Flared 10^6 Tons/yr	$\frac{10^6 \text{ MBtu}}{\text{Yr}}$
Refineries	1048	0.2	2.1	103
Petroleum Production	584	0.5	2.9	116
Blast Furnaces[a]	146	6.6	9.6	69
Coke Ovens[a]	55	0.4	0.2	11
Chemical Industry[a]	60	2.0	1.2	59
		Total	16.0	358

[a] Combustible gases only

2.2 Emissions From Flares

The first objective of any future study on flares is to establish their combustion efficiencies. Emissions factors have been previously estimated or measured (Bartelds, 1981; Siegel, 1980; Becker, 1974). Many of the efficiencies estimated for flares have been very high (99+ %); however, some estimates range to as low as 50 percent. Theoretical estimates of efficiencies cannot be used for establishing emission standards. Emissions from commercial flares have not been measured, and measurements from previous pilot studies are suspect for reasons discussed in subsequent sections.

A logical conclusion is that efficiencies from flares are unknown, with present estimates varying by as much as a factor of two. Part of the reason is that measurements are difficult to make on large elevated flares. In addition, the data are extremely difficult to interpret because of the intermittent nature of the flame, the accuracy of measuring low concentrations of incompletely burned hydrocarbons, and the difficulty of measuring and summing all small losses from the flame.

In the United States, flare operations are controlled to the extent that they do not emit visible smoke during "normal" operations. This restriction does not apply to "emergency" flaring. In any event, the emission of gaseous products is not monitored. Therefore, there is no data on industrial flare emissions. As a result of the lack of information, the German governmental regulatory agency (TA-Luft) assumed all elevated flares to be 75 percent efficient for the purpose of regulating flare installation and use. As will be shown in later discussions, this efficiency is one of the lowest estimates and is no more reliable than other estimates. Moreover, data from pilot scale flare experiments suggest that emissions from flares depend on the characteristics of the gases flared and the operating conditions of the flare. This is reflected in a recent Dutch study included as Appendix D. These data are fragmentary and will be discussed in more detail in later sections of this report. The lack of conclusive data precludes accurate estimates of emissions from industrial flares.

2.3 Commercial Flares

The performance and emissions of flares are controlled largely by the fuel burned and the mechanisms designed to improve mixing in the flare. Design of the nozzle is thought to be crucial to flare stability, turndown ratio and suppression of soot. However, the actual nozzle design is thought to have only a small effect on the structure of typical low-momentum buoyant flames.

This section will discuss the design of commercial flares, the effect of the fuels burned on flare performance, the operating conditions of commercial flares, and the size and capacity of commercial flares. This information will be used as a basis for the selection of pilot scale flare designs and experimental operating conditions which cover the range of variation in commercial flare operation.

2.3.1 Design of Flares

This section will discuss the major types of flares, the design criteria for elevated flares, and procedures used to design commercial flares. The purpose of this discussion is to ensure that experimental flares to be used in this program adequately simulate the design of commercial systems.

There are two major types of flare configurations: Elevated (Figure 2-3) and Ground Flares (Figure 2-4). The cost of constructing and operating, use, capacity, and emissions of ground and elevated flares are considerably different.

Elevated flares are more numerous and have larger capacities than ground flares, and typically consist of a flare stack and one or more elevated flare tips which stabilize the flame. The flame is exposed to atmospheric disturbances such as wind and precipitation. A ground flare consists of an enclosure which confines the flame. The number of burner heads in a ground flare will vary with the capacity of the ground flare, and since the flame is enclosed, it is not affected by wind. Ground flares require more equipment, cost more, and hence are infrequently used to flare large amounts of gas.

Ground flares are typically used to dispose of small amounts of gas continuously while elevated flares are used to dispose of large amounts of gas released in emergencies. The difference in capacity is shown in Table 2-10. The differences are caused not only by the cost of ground flares but by the poor turndown ratio of ground flares compared to elevated flares.

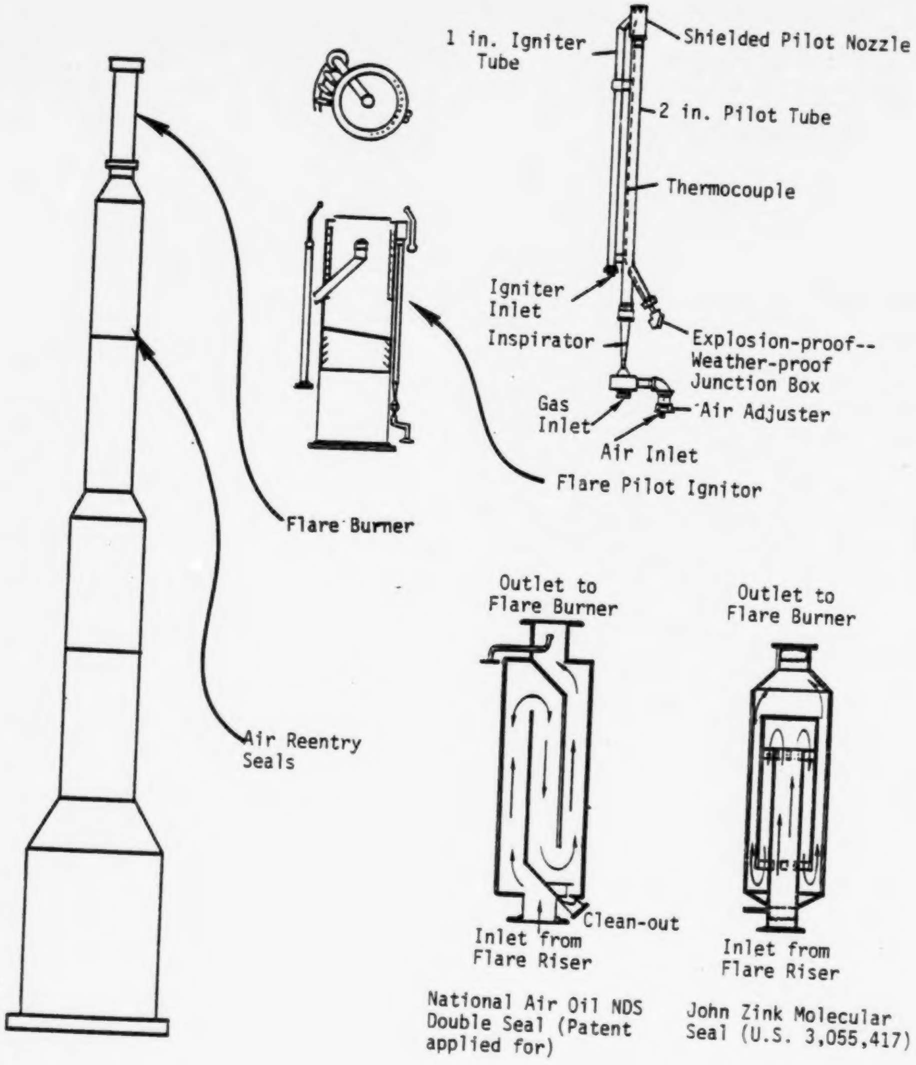
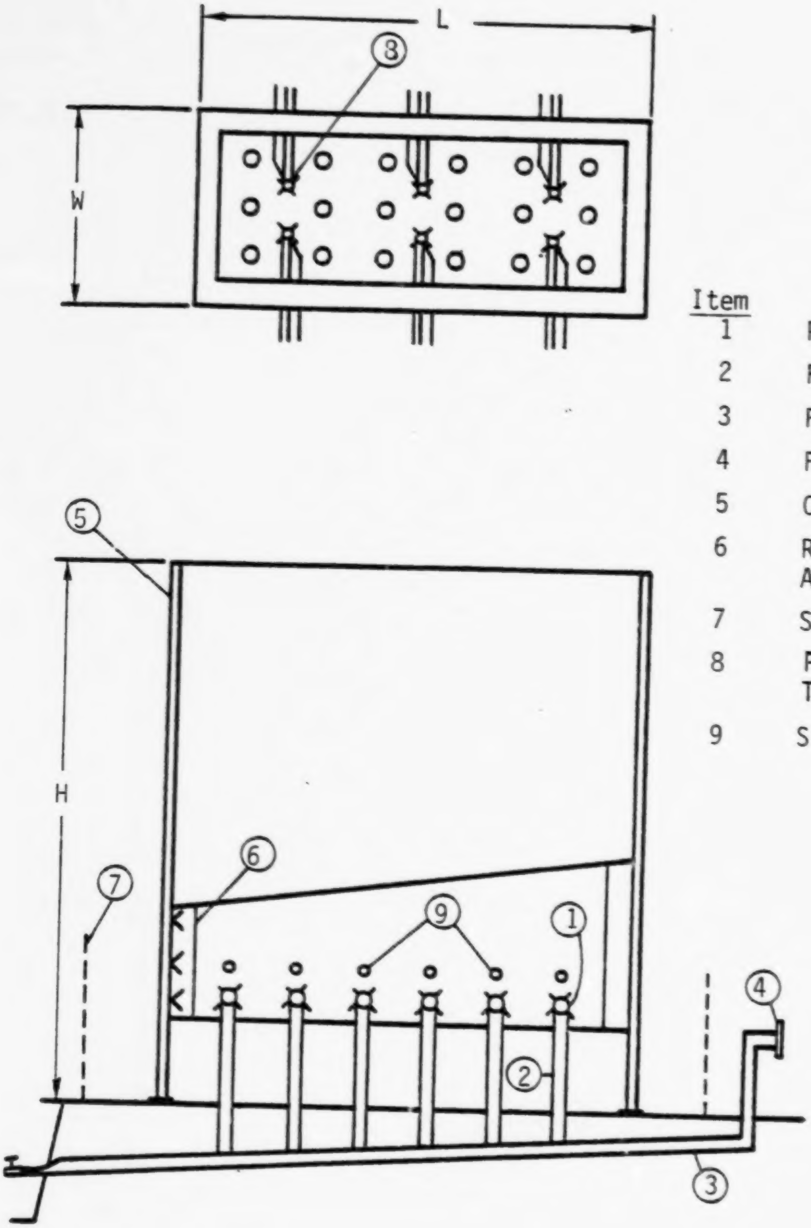

1 in. Igniter Tube
Shielded Pilot Nozzle
2 in. Pilot Tube
Thermocouple
Igniter Inlet
Inspirator
Explosion-proof--Weather-proof Junction Box
Gas Inlet
Air Adjuster
Air Inlet
Flare Pilot Ignitor
Flare Burner
Outlet to Flare Burner
Outlet to Flare Burner
Air Reentry Seals
Clean-out
Inlet from Flare Riser
Inlet from Flare Riser
National Air Oil NDS Double Seal (Patent applied for)
John Zink Molecular Seal (U.S. 3,055,417)

Figure 2-3. Components of an elevated flare (Klett & Galeski, 1976).



Item	Description
1	Patented Jet Mix Tips
2	Flare Gas Riser
3	Flare Gas Header(s)
4	Flare Gas Connection(s)
5	Combustion Chamber
6	Refractory Lining and Anchors
7	Safety Fence (Collapsible)
8	Pilots with Igniter Tubes
9	Sight Ports

Figure 2-4. Rectangular multi-jet ground flare (Klett & Galeski, 1976).

TABLE 2-10. CAPACITY OF DIFFERENT FLARE TYPES

Type of Flare	Capacity lb/hr
Ground	80,000-100,000
Forced Draft Elevated	100,000
Natural Draft Elevated	1,000,000-2,000,000

Elevated flares typically operate with a turndown ratio of up to 1000.

Ground flares produce less emissions than elevated flares (Kalcevic, 1980). This is attributed to many well-aerated low velocity gas jets. In addition, the enclosure reduces flame radiation loss allowing longer time at reaction temperatures. Government bodies in the FRG consider ground flares to burn fuel with 95 percent efficiency while elevated flares are assumed to burn fuel with only 75 percent efficiency (DMGK, 1980). Because of their cost effectiveness and wide operating range elevated flares dispose of the majority of waste gas. Consequently, future programs to quantify emissions from flare flames should emphasize elevated flares.

The design of elevated flares is dictated by the desire to:

- Operate the flare safely over a wide range of gas flow rates.
- Have acceptable emissions of radiation, toxic and flammable materials and noise.

A number of flare design aspects must be considered to safely operate a flare over a velocity range from 0.2 ft/sec to 600 ft/sec. The flare stack must be isolated from the process to avoid influence of stack operation, including explosions, on the process. Any large liquid droplets entering the stack must be removed or they will fall incompletely burned from the stack. Air must be excluded from the stack, particularly during operation at low velocity, to avoid explosions, the flame must be ignited and burn stably on the tip to avoid flashback or blowoff. Means for mixing air into the flare must be provided for most fuels if soot is to be suppressed. The stack must be high enough so that the radiation flux to areas accessible to personnel is tolerable, and so that flammable and/or toxic gases to not descend to ground levels in dangerous concentrations.

The flare stack is usually isolated from the gas collection system and the process. This is commonly achieved by use of a water seal, although flame arrestors have been used. Flame arrestors are infrequently used because they tend to plug and are inefficient in quenching hydrogen, acetylene, ethylene oxide and carbon disulfide flames. Water seals are frequently used but are typically located near ground level because of their weight. This arrangement potentially leaves the entire stack as a reservoir which can be filled with explosive gases. Air seals are usually provided to prevent air leakage into the stack.

Separation systems are used to remove large liquid drops from the gases to be flared. The separating systems are sized so that the velocity is low enough that small liquid drops are removed by gravity.

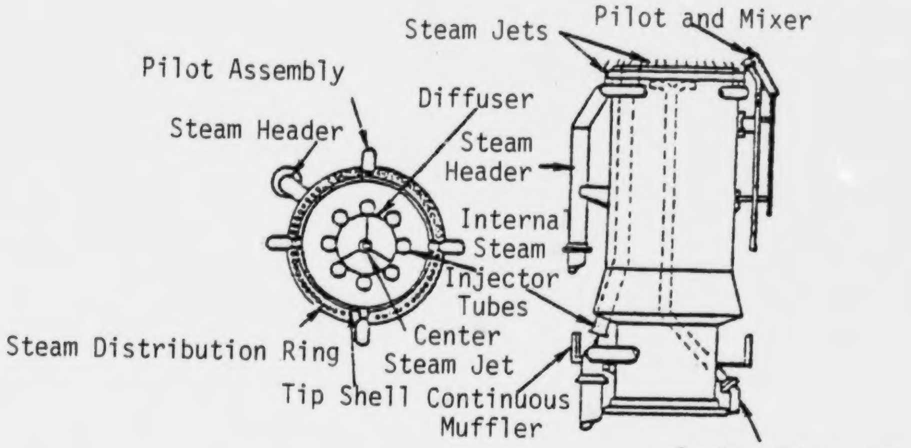
Air seals and purge gas are used near the tips of flares to exclude ingress of air into the stack. Many designs of air seals exist: Two are shown in Figure 2-3. Air seals are designed to increase the velocity of gas near the tip of the stack so that diffusion of air into the stack is more difficult.

The flare tips are designed to stably burn gases over a very wide range of flowrates and to suppress soot. The design of tips is proprietary, hence details of tip design are rarely available. However, schematic designs of some tips are available and are shown in Figure 2-3 and 2-5. Flare stability is ensured by the use of proprietary flame holders and pilot flames.

The method of air entrainment directly affects the sooting behavior of the flare. Hence, elevated flares are distinguished as non-smokeless and smokeless, depending on the fuel flared and the design of the flare nozzle. Non-smokeless flares have no smoke suppression devices, and are used to burn non-sooty gases such as H_2, H_2S, CO, etc. Smokeless flares incorporate steam injection, Coanda nozzles, air injection or other devices to improve air entrainment and mixing, and are necessary for gases with a high smoking tendency.

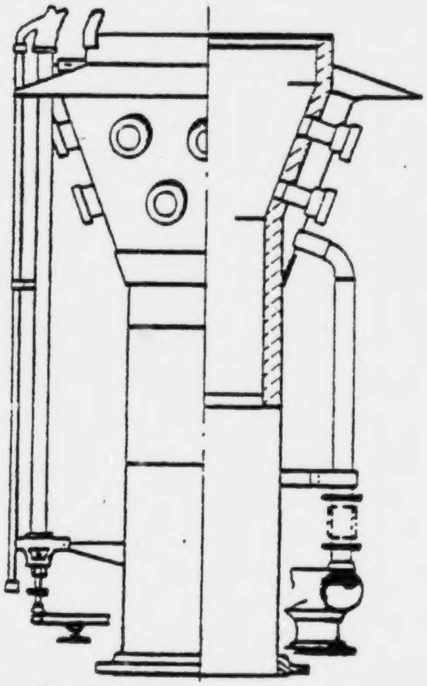
There is no information available in the public literature concerning the design criteria of flame holders and smoke suppression devices. However, there are methods available to calculate nominal flame size and the elevation of the flare head (Oenbring and Sifferman, 1980).

Nozzle tips are sized so that the maximum velocity of the gas does not exceed a Mach number of 0.2 for continuous flaring and 0.5 for emergency flaring. This relationship is empirical and, according to many designers, flexible. The height of the stack is set by the need to reduce either the radiation flux or the concentration of toxic or flammable gases to safe levels at the ground. The radiation from the flames is empirically calculated using a factor to account for the emissivity of the flame.


Pilot and Mixer
Steam Jets
Pilot Assembly
Diffuser
Steam Header
Steam Header
Internal Steam Injector Tubes
Steam Distribution Ring
Center Steam Jet
Tip Shell
Continuous Muffler
Center Steam Jet

Steam Injection Flare Tip

PLAN ELEVATION



Coanda Flare Tip

Figure 2-5. Design of flare tips
(Klett & Galeski, 1976).

As an example, the size and elevation of a flare are calculated for disposal of 32.4 Mscf/d (1.35 M scfh) of gas at 46°F with the composition listed in Table 2-11. The nozzle tip is sized for a Mach number of 0.2. The sonic velocity is calculated from:

$$u_s = 223 \sqrt{\frac{c_p / c_v \ T}{M}} = 1{,}399 \text{ ft/sec}$$

The exit velocity is then:

$$u_o = 0.2 \ (1{,}399) = 280 \text{ ft/sec}$$

and the actual volumetric flowrate at the tip is:

$$\dot{V}_o = \frac{\text{SCFH(T)}}{1.872 \times 10^6} = 364.9 \text{ ft}^3\text{/s}$$

The diameter of the tip is easily calculated from the above values:

$$d = 12 \sqrt{4/\pi \ \frac{\dot{V}_o}{u_o}} = 15.46 \text{ in.} \sim 16 \text{ in.}$$

The flare head must be located such that under no condition will the flame impose harmful thermal radiation loads on nearby personnel and equipment. It should also be located high enough so that in the event the flame is extinguished, hazardous levels of flammable or toxic gases do not reach the ground. The ground level thermal load depends on the flame length, the heat available, the emissivity of the flame and the location of the flame. The ground level gas concentrations depend on the gas flowrate, wind and height of the flare stack.

There are many empirical relations to estimate the length of turbulent flames. Most of these are based on a very limited set of data and cannot account for the effects of steam addition, air mixing, or crosswind on flame length. The results from several of these techniques were compared with measured lengths of a flare at different velocities (Oenbring and Sitterman, 1980). Brzustowski's formula was found to agree best with the measured flare lengths and was suggested for calculating flame heights. However, the Brzustowski formula is the most complicated and underestimated the flame length at all velocities. The flame length calculation for this example is:

TABLE 2-11. PROPERTIES USED IN EXAMPLE OF FLARE DESIGN

Flow rate	32.4 M scf/d $\sim$ 1.35M scf/h continuously
Temperature	46°F
Wind speed	5 mph
Composition	Mole percent
CO_2	0.86
N_2	0.30
CH_4	95.71
C_2H_6	2.94
C_3H_8	0.16
i-C_4H_{10}	0.02
n-C_4H_{10}	0.01
	100.00
Derived Quantities	
Molecular Weight	16.8
Lower Heating Value	923 Btu/scf
Temperature	506°R
c_p/c_v	1.307

Calculate the dimensionless lean limit concentration ($\overline{C_L}$)

$$1/C_L = \sum \frac{Y_i}{C_{L_i}} = \frac{1}{0.049}$$

$$\overline{C_L} = 1/C_L \quad \frac{u_o}{u_w} \quad \frac{M_o}{M_a} \quad = 1.09$$

Since $\overline{C_L} > 0.5$

Calculate the dimensionless streamwise coordinate, $\overline{S_L}$

$$\overline{S_L} = \frac{2.51}{(\overline{C_L})^{0.625}} = 2.38$$

Since $\overline{S_L} > 2.35$

Calculate the dimensionless downwind coordinate $\overline{X_L}$

$$\overline{X_L} = \overline{S_L} - 1.65 = 0.73$$

Calculate the dimensionless flame length $\overline{L_F}$

$$\overline{L_F} = 2.05(\overline{X_L})^{0.28} = 1.88$$

Calculate the square root of the ratio of the jet momentum to the wind momentum

$$R = \left(\frac{u_o}{u_w}\right)\left(\frac{\rho_f}{\rho_a}\right)^{\frac{1}{2}} = 30.2$$

Calculate the dimensional coordinates of the flame

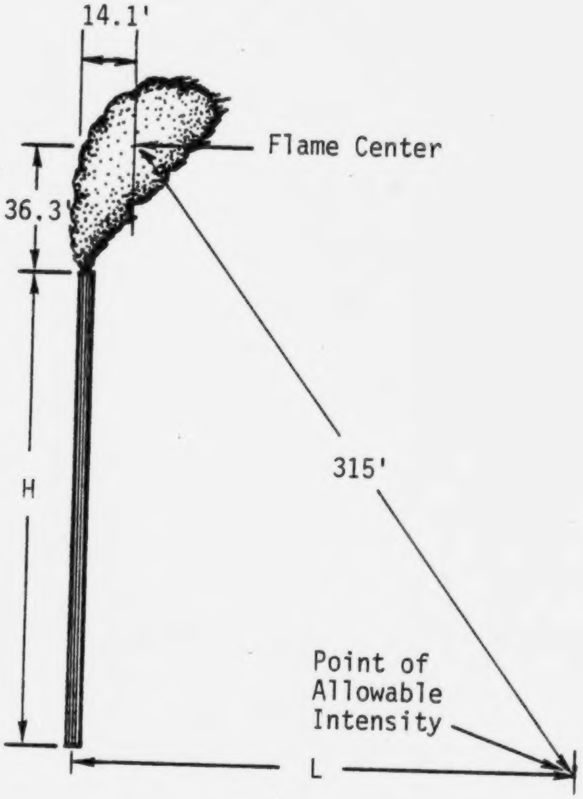
$$L_F = \overline{Z_L}\, d_o R = 72.7 \text{ ft}$$

$$X_L = \overline{S_L}\, d_o R = 28.2 \text{ ft}$$

Therefore, the flame is 72.7 feet long and the center is displaced 14.1 feet downwind from the centerline of the stack (Figure 2-6).

To simplify thermal flux calculation, the flare flame is approximated by an equivalent radiating point source assumed to be at the geometric center of the flame. At any point, the radiation heat flux is

$$K = \frac{FQ}{4\pi D^2}$$


14.1'
Flame Center
36.3'
H
315'
Point of Allowable Intensity
L

L, horizontal distance from base of stack to point of allowable radiation intensity (ft)	H, required stack height (ft)
100	267
200	218
300	96

Figure 2-6. Stack height and allowable radiation intensity (Oenbring and Sitterman, 1980; used with permission from HYDROCARBON PROCESSING, May 1980).

where

F = fraction of total heat radiated

Q = total heat content of flared gas

D = distance from equivalent point source of radiation

For this example, the tolerable radiation flux for humans for an infinite period is about 600 Btu/hr ft^2. This flux includes a solar flux of 350 Btu/hr ft^2, so the allowable radiation flux from the flame is 250 Btu/hr ft^2. The factor F is 0.25 for methane and ranges from 0.4 to 0.5 for heavier gases. For this example, F is estimated as 0.25. Total heat content of the flared gas, Q, is 1.246 x 10^9 Btu/hr. Therefore

$$D = \sqrt{\frac{FQ}{4\pi K}}$$

$$D = \frac{(0.25)(1.240 \times 10^9)}{(4)\ (250)} \text{ ft}$$

$$= \quad 315 \text{ feet.}$$

The relationship between stack height and the point of allowable radiation intensity is shown in Figure 2-6.

The above calculation is not precise for two reasons: First, the calculation of the center of the flame is inaccurate and, second, the fraction of the heat release radiated from flares can vary. Measurements of the radiation emissivity factor for a methane flare varied from 0.19 to 0.28 and may vary from 0.10 to 0.89 for a flame of unknown composition. Errors in these calculations can thus be considerable.

The stack height can also be controlled by the acceptable level of flammable or toxic gases at the ground. The gases issuing from the flare can be hazardous because they are flammable or because they are toxic combustion products. The necessary height of the stack is calculated based on the equations for plume dispersion. These are well known and have been reviewed by Reed (1968) and Turner (1969). However, the calculated ground level concentration of substances can be erroneous by a factor of three or greater.

Flares can generate noise at uncomfortable levels. Measurements on flares show that noise can be as high as 100 db-c at locations accessible to personnel. Noise from flares is generated as high frequency jet noise by the injectors, low frequency turbulent combustion noise generated by the flame and very low frequency noise caused by vibrating water seals. Jet noise caused by the steam injectors can be reduced by designing lower velocity injectors. Combustion noise can be modified to some extent by proper tip design, and noise created in the water seal can be nearly eliminated by modification of the design.

The final aspect of design is to suppress soot formation by improving the mixing of air into the flame. This can be done in five ways:

1. By injecting steam jets into the bottom of the flare.
2. By injecting natural gas into the flare.
3. By injecting water into the flare.
4. By designing the flare tip to improve mixing, for instance, by using the Coanda effect.
5. By supplying air with a forced draft system.

Injection of steam is the most popular technique and, in general, the least expensive technique to suppress soot (Table 2-12).

Flares are currently designed by proprietary empirical methods in order to:

- Safely burn gas discharged at widely variable flow rates.
- Prevent ingression of air into the stack.
- Suppress formation of soot.
- Separate liquid drops from the gas stream.
- Isolate the flare stack from the rest of the process.
- Burn gases without producing a hazardous radiation flux to the ground.
- Ensure that the concentration of hazardous materials is below the danger threshold at ground level.

TABLE 2-12. RELATIVE COST OF SUPPRESSING SOOT IN FLARES (KLETT & GALESKI, 1976)

Type of Flare	Equipment Costs 12-in. Diam.	 24-in. Diam.
Smoking		
Standard Tip	1.00	1.00
Smokeless		
Steam Tip	1.25	1.25
Gas Tip	1.30	1.30
Water Tip	1.20	1.20
Forced Draft	2.80	3.38

2.3.2 Fuels Flared

The composition of the fuels affects the design, operation, emissions, stability, and turndown capability of flares. The following fuel properties are thought to affect the performance of flares:

- Flammability limits
- Auto-ignition temperature
- Heating value
- Density
- Sooting potential (C/H)

These properties for some fuels flared are shown in Table 2-13.

The flammability limits of the gases flared influence ignition stability and flame extinction (gases must be within the flammability limits to burn). Hence, in the interior of the flame and near the nozzle, insufficient air exists for the mixture to burn, and outside the flame so much air may have been induced that the flame is extinguished. Fuels with wide limits of flammability are usually easier to burn, for instance, H_2 and acetylene. However, in spite of wide flammability limits, CO is difficult to burn because it has a low heating value, high product heat capacity and slow combustion kinetics.

The auto-ignition temperature affects the combustion of fuels because gas mixtures must be at high enough temperature and at the proper mixture strength to burn. A gas with low auto-ignition temperature will ignite and burn more easily than a gas with a high auto-ignition temperature. Again, H_2 and C_2H_2 have low auto-ignition temperatures while CO has a high one.

The heating value of the fuel also affects the flame stability, emissions, and structure. A lower heating value fuel produces a cooler flame which is more easily extinguished. The lower flame temperature will reduce buoyant forces, mixing, and will tend to increase the levels of unburned hydrocarbons. The emissions for flares burning gases with low Btu content should, therefore, be considered because the emissions may be higher than those from flares which burn high Btu gases.

TABLE 2-13. PROPERTIES OF FUELS FLARED

Fuel	Density lb/ft^3 @ 298K	Low Heating Valve Btu/ft^3	C/H	Auto Ignition Temp ^oK	Flammability Limits Volume %
H_2	0.0052	268.5	-	811-867	4.1 - 74.
CO	0.072	314.7	-	922	12.5 - 75.
CH_4	0.042	1011.6	1/4	905	5.3 - 14.
C_2H_2	0.069	1483.8	1	589-700	2.5 - 80.
C_2H_4	0.072	1608.5	1/2	763	3 - 29
C_2H_6	0.078	1783.7	1/3	746	2.8 - 15.3
C_3H_8	0.117	2563.3	3/8	811-867	2.1 - 11.4
HCN	0.070[a]	715.	1	811	5.6 - 40.
NH_3	0.044	217.	-	922	16 - 27

a - Liquid at STP

Some fuels also have chemical differences sufficient to alter the emissions from flares. For instance, CO is difficult to ignite and burn and consequently may lead to greater emissions of incompletely burned fuels than hydrocarbon fuels.

Density of the gas flared also affects the structure and stability of the flame through the effect of buoyancy. The velocity in many flares is very low. Therefore, most of the flame structure is developed through buoyant forces on the hot burning gas. The density of flared fuel can vary by factors of two to four. Density of the fuel also affects the minimum purge gas required to prevent flashback and the design of the burner tip.

The tendency of a fuel to soot is affected by the mixing conditions of the flare head as well as the fuel characteristics. The propensity of hydrocarbon fuels to soot is qualitatively related to the carbon/hydrogen ratio. Qualitative inspection of Table 2-14 indicates that fuels with C/H ratios greater than 0.35 tend to soot (Mandell, 1978).

Gases flared are of two basic types: High heating value hydrocarbon based gases and low heating value carbon monoxide based gases. Some toxic gases are also flared, but the above two categories cover most of the gases flared. The composition and quantity of gases flared has been covered in Section 2.1 and Tables 2-1 through 2-8. The petroleum refinery, petroleum production, coke production, and the chemical industry largely flare high-Btu-content hydrocarbon gases, while blast furnace production flares low-Btu-content gases which contain large amounts of carbon monoxide. Sixty percent (by weight) of the gases flared in the United States are low-Btu-content blast furnace gases. However, this corresponds to only 19 percent on the basis of heat content.

2.3.3 Flare Operating Conditions

This section discusses operation of flares. The discussion will identify the important operating conditions of commercial flares: The use of elevated and ground flares, the capacities and velocities of each, and the use of steam to suppress soot. These conditions will then be used to suggest design and operation of small scale flares to represent commercial flares.

TABLE 2-14. SOOTING TENDENCIES OF FUEL (MENDELL, 1978)

Fuel	C/H	Flame Appearence
C_2H_2	1	extremely black
C_3H_8	0.38	black
C_2H_6	0.33	light soot tailing
CH_4	0.25	no soot

Flares operate both continuously and intermittently over a very wide range of flow rates. Klett and Galeski (1976) estimated that 90 percent of the gases burned were flared at 10 percent or less of the maximum capacity of the flare. It is assumed the other 10 percent was burned with the flare operating at 100 percent of capacity, or under emergency conditions.

Waste gases which are continuously flared are derived from different sources than those which are intermittently flared. Waste gases that are continuously flared come from oil wells, small bleeds and leaks, and relative continuous transfer and loading operations; those that are intermittently flared result from process upset, relief of pressure valves, and other unexpected conditions.

Flare tips are sized based on a fraction of sonic velocity. Industry recommends that the Mach number not exceed 0.2 for continuous flaring and 0.5 for intermittent flaring. For the example presented in Section 2.3.1 then, a 16-inch flare, which flared 1.35 Mscfh of gas continuously, could flare up to 3.4 Mscfh of gas intermittently.

Most waste gases are burned in elevated flares. During normal operation, the flare may burn at 1 percent or less of its maximum capacity. In such cases, the exit gas velocity may be as low as 0.15 ft/sec. While at full operation, the exit gas velocity can reach 600 ft/sec or more. This would yield a turndown ratio of 4000 which is typical of elevated flare operation. However, nominal maximum design velocity is between 300 and 400 ft/sec (Klett and Galeski, 1976).

The only operating condition of flares which can usually be controlled is the means used to suppress soot formation. Smokeless flares employ ways to mix the flare gas with air before ignition. There are several ways to do this:

- Forced draft
- Steam injection
- Air injection
- Water injection
- Coanda mixing

In a forced draft arrangement, the flare stack consists of two coaxial flow channels. The combustible gases flow in the center channel and the combustion air flows in the annulus. Mixing of the fuel and air is promoted at the flare tip and the mixture is ignited. Forced draft is rarely used on large flares because it is expensive and air flow is difficult to control when the gas flow is intermittent. Forced draft flares typically burn less than 1 Mscfh of gas and cost about 3 times as much as elevated flares (Table 2-11). About 0.8 hp of blower capacity is required for each 100 lb/hr of gas flared (Klett and Galeski, 1976). A 50 hp blower would then be required to burn 1.35 Mscfh of gas in the example given in Section 2.3.1.

Injection of low pressure steam to draw air into the fuel is another way of promoting mixing. Steam does not appear to chemically affect the flame, but is used because it can induce air into the flame efficiently and is normally readily available in industrial plants.

Other variations of steam injection are also used. Steam can also be injected in the center of the flare stack below the tip and used in separation nozzles to increase air entrainment and reduce steam usage (Figures 2-3 and 2-4). Steam required to suppress soot depends on the injection arrangement as well as the fuel properties (e.g., C/H ratio). Typically the steam required to eliminate smoke varies from 0.2 to over 1 lb of steam per lb of gas flared. However, the general trend of industry is to minimize the amount of steam used.

An empirical formula is available to predict steam and air flow requirements for suppression of soot (Klett and Gasleski, 1976).

$$\frac{\dot{m}_{st}}{\dot{m}_{HC}} = \alpha - 10/M_f$$

where

M_f = average molecular weight of flared gas

α = 0.5 for paraffins heavier than propane and 0.6 for olefins

The formula is accurate to within ± 25 percent. Use of the formula to predict the amount of steam required for the example of Section 2.3.1 by assuming propane was flared instead of methane gives a steam requirement of 0.27

pounds of steam per pound of fuel.

Air can also be injected to control soot. However, air requirements to control soot are higher than steam requirements. The above formula can be used to predict air requirements by changing α to 0.55 for paraffins and 0.69 for olefins. The air requirement for the above example is then 0.32 pounds of air per pound of gas.

Injection of water to suppress soot formation is not recommended for elevated flares. Water injection is less efficient than steam, provides a limited turndown ratio, can quench the flame at low loads, and can freeze and corrode the stack. Typically 1.0 to 1.2 pounds of water are required per pound of gas to suppress soot formation.

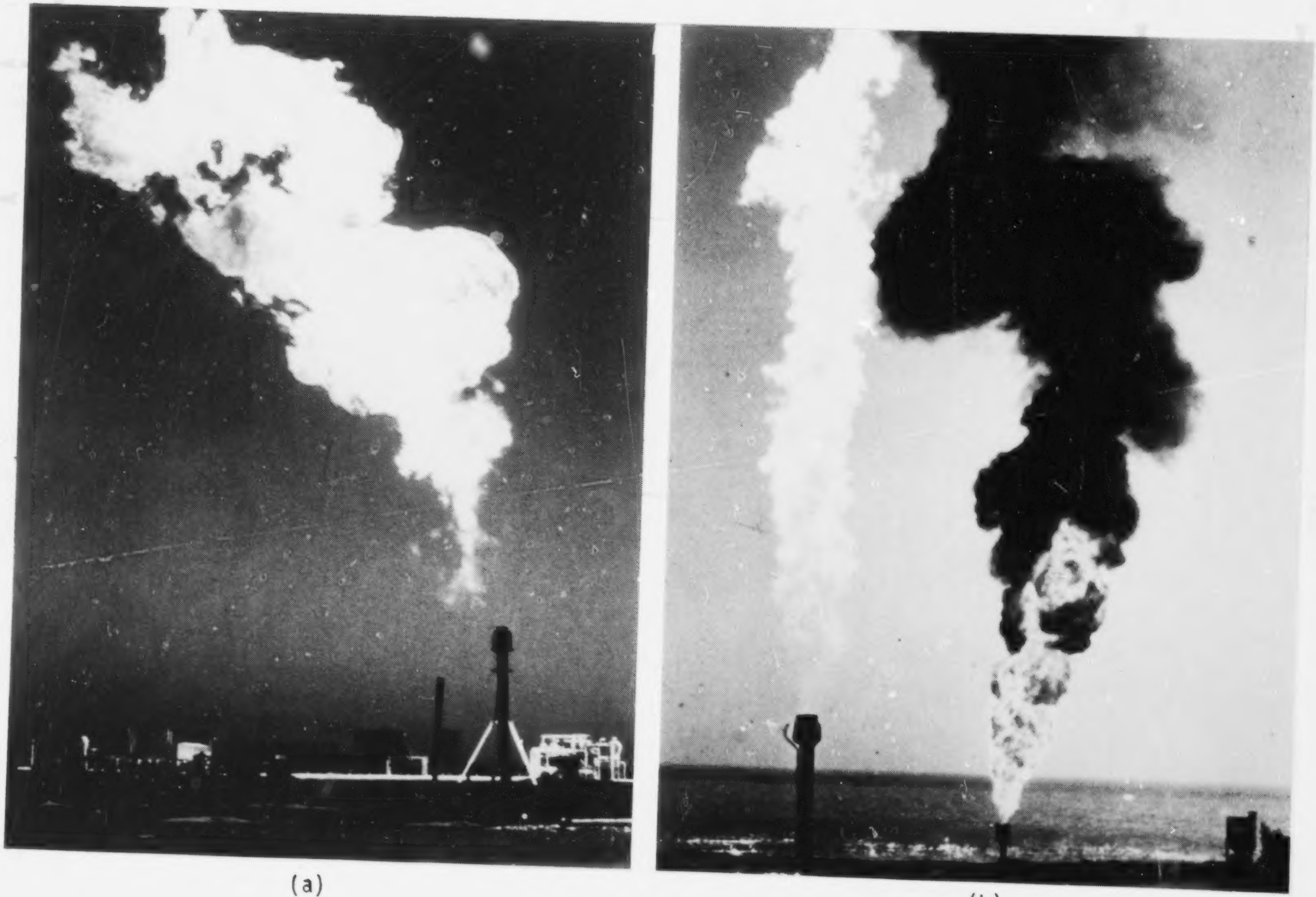
Mixing of air into the flare can also be increased by the aerodynamic design of the nozzle. The Coanda nozzle is an example of this in commercial flares (Kaldair, 1979, and Figure 2-7). The flare on the left of Figure 2-7b shows the efficiency of the Coanda effect in suppressing soot.

Crosswind velocity will effect flare performance and emissions. The known effects of crosswinds are discussed in Sections 2.4.6 and 2.5.2. Basically an increase in crosswind distorts the flame downwind. At low velocities, the wind increases the mixing and shortens the flame length. At higher velocities, it decreases the mixing, increases the flame length, and strips eddies from the flame. Experimental evidence (Brzustowski, 1975 and 1977) and theoretical calculations (Escudier, 1972) indicate that the visible flame length is shortest when the ratio of wind velocity to flare velocity is from 0.01 - 0.1 and the visible flame length is unchanged with a ratio above 0.1 - 0.2.

2.3.4 Flare Size and Capacity

This section reviews the available information on capacity, size, heat release, and velocity of flares. This information is required so that small scale flares can be designed to simulate the important design and operating parameters of commercial flares.

The capacity of a flare is set within limits by the need to dispose of the process gases. Flares have been built to burn 25 Mscfh of gas. Once



(a)

(b)

Figure 2-7. Commercial flare heads. (a) 20 Mscfd pipe flame; (b) 60 Mscfd smokeless flare and a 20 Mscfd smoky flare. (Reproduced with permission from Peabody/Kaldair, 1979.)

the required capacity of the flare has been established, the diameter of the nozzle is calculated by the methods of Section 2.3.1 so that the Mach number is less than 0.2 for continuous flaring and less than 0.5 for emergency flaring. Using these criteria, velocities between 1 to 600 ft/sec are typical. Nominal maximum design velocities are between 300 to 400 ft/sec. Excessively high velocities (600 ft/sec) may cause the flame to lift off and excessively low velocities (0.15 ft/sec) may cause the flame to flashback. In addition, velocities below 0.15 ft/sec may allow ambient air to leak into the stack which may result in an explosion. Improved flare tip seals have reduced the lower gas velocity limit to 0.03 ft/sec (Kalcevic, 1980). Based on the velocity constraints and typical flare gas flow rates, commercial flare tips vary from 0.4 m (16 in) to 1.8 m (6 ft) in diameter. However, flares as small as 1-1/2 inches and as large as 12 feet in diameter have been used. In 1980, the California Air Resource Board surveyed the refineries in California (Table 2-1 and Figure 2-8). The information supplied by the refineries that responded to the survey showed that the most common size flare in refineries is around 3 to 4 feet in diameter. Figure 2-8 shows the distribution of flare sizes for the survey response.

The heat release rate of flares can be very large. The rate for the largest flares may be as high as 20×10^9 Btu/hr. In addition, at maximum flows, flares are more likely to be inefficient and smoky because insufficient steam is available to suppress soot production. According to Kalcevic (1980), the capacity limit for smokeless combustion is about 300,000 lb/hr (propylene) for a 60 inch diameter flare. Generally, smokeless operation is limited to about 20 percent of full flare capacity.

The capacity of flares which depend on steam, water or air injection for smokeless operation is further limited by the maximum supply of these utilities. Injection of air is usually not as effective as air induced by steam injection. Water is rarely injected into elevated flares because about 2 to 3 times as much water as steam is required to produce smokeless flames. Also, water can corrode the stack, particularly if the gas flared contains acid gases.

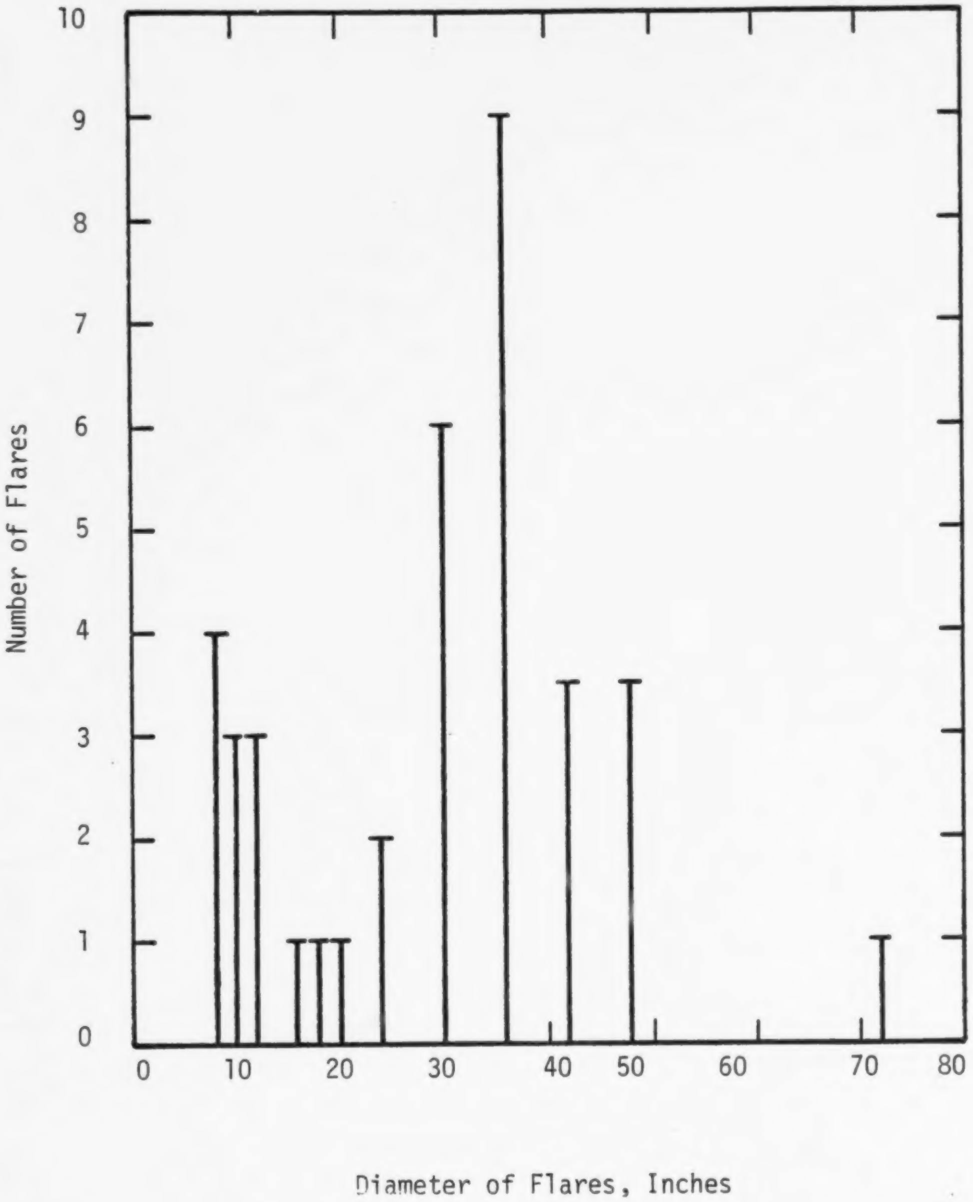


Figure 2-8. Distribution of flare nozzle sizes reported by California Refineries to California Air Resource Board Survey (1980).

2.3.5 Summary of Commercial Flares

The design and operation of commercial flares has been reviewed so that small scale flares can be designed which are representative of large scale systems. The design of commercial flares is based largely on the limiting Mach number of 0.2 at the nozzle for smokeless operation. Small scale flares can and should use the same design criteria.

Use of the Mach number criteria results in maximum velocities for emergency flaring (Mach number ~0.5) of about 600 ft/sec. Velocity can also be as low as 0.2 ft/sec in nozzles. About 90 percent of the gases flared are burned at less than 10 percent of the maximum velocities or between 30 and 60 ft/sec. Baseline conditions for experimental studies should use velocities in this range. Velocities outside of this range should also be investigated, but to a lesser extent.

The nozzle must be scaled to a manageable size from the commercial size. Commercial nozzles vary in size from 1-1/2 inches to 12 feet. The smaller commercial nozzles, 1-1/2 to 12 inches, are appropriate for experimental studies and will provide geometric similarity with the larger commercial nozzles.

Gases burned in flares are of two types: Light hydrocarbon gases with heating values above 700 Btu/ft^3 and a mixture of carbon monoxide and inert gases with a heating value of around 90 Btu/ft^3. Most of the heating content of gases flared are of the former type while most of the weight of gases flared are the latter. A light hydrocarbon fuel which soots diluted to a heating value of about 1000 Btu/ft^3 should be used as the baseline fuel. The effect of burning a low heating value carbon monoxide gas and a low heating value hydrocarbon gas should be studied. The effect of C/H ratio for hydrocarbon fuels on flare performance and emissions should also be investigated.

Commercial flares frequently use steam to suppress soot. Typically, about 0.2 - 0.3 pounds of steam per pound of gas are used, but information from Siegel indicates that a ratio of about 0.5 is optimum. The effect of steam injection at various levels on flare structure and emissions should be investigated.

Wind conditions alter the mixing patterns, flame structure, and temperature of flares. Hence, the effect of wind on flare performance needs to be investigated. Experimental wind velocities should be chosen to be in the normal range of atmospheric conditions. Wind velocities which will affect flare performance for the recommended velocities of commercial flares would be in the range of 4 - 12 mph.

2.4 Experimental Information on Flares

The main object of previous work carried out on flares was to determine emissions and the effect of operating parameters on these emissions. However, a review of the open literature revealed little useful data on emissions from flares. Notable studies are those by Palmer, Siegel, Lee and Whipple, and Howes, et al. Siegel studied a small refinery flare. Howes, et al, worked with John Zink air assisted and LRGO flares to develop measurement techniques. The other investigator studied pilot-scale flares. Data from these studies shed light on some of the characterisitcs of flares, and some of the measurement problems involved, while field data on emissions from elevated flares are almost nonexistent. Today, still no information has been published which would allow the emissions of industrial flares to be accurately estimated.

The problem of accurately estimating emissions from flares can be attributed to several factors:

- Sampling is difficult because elevated flares can be 250 feet above the ground and the flames can be several hundred feet long.
- Flare operation can be transient because discharge of the gas is unscheduled.
- Flare flames fluctuate spatially and temporally and are affected by uncontrollable atmospheric disturbances.

The pilot scale experiments provided preliminary information on the effects of flare operating parameters. Although many of these experiments were performed at scales considerably smaller than field units, sampling remained a problem. In some studies, tracers have been used to improve the techniques used to characterize emissions from flares. However, closure of the mass balance around the flame remained poor.

The previous studies on flares (Table 2-15) have addressed the emissions of incompletely burned material, the distance required to burn the flared material, the effect of the use of steam injection on emissions, and the effect of wind on emissions. Results from these studies are reviewed in the following sections to provide the relevant background material for the present study and to identify information gaps which affect both our understanding of large open turbulent diffusion flames and our ability to make representative measurements.

The results from the previous studies have made valuable contributions to the knowledge of flare performance. However, the problems of measuring or modeling flares are extremely difficult. While the previous studies were able to define some general aspects of flare flames and to identify the major problems in taking measurements of flare flames, none could accurately determine the emissions from flares. This is urgently needed and remains to be done.

In addition to the flare studies, a number of studies on cold jets, turbulent flames, and pool flames have produced information useful to modeling and scaling flares. These results will be discussed in the section on modeling and scaling.

2.4.1 Flare Characteristics

In the absence of crosswinds and air injection, a flare flame is a jet diffusion flame. The incoming gas ignites when it is mixed with sufficient oxygen and heated above its reaction temperature by recirculation of hot products. Photographs of two flare flames (Figure 2-7) show many of the typical characteristics: Large stand-off distances, large eddies, flamelets separated from the flame and internal eddies apparently burning with different intensities. The flame on the left in Figure 2-7b is not smoking, although some flares can produce large amounts of soot as the flare on the right in Figure 2-7b.

The mixing between the gas and the ambient air in flares is affected by the jet exit velocity, the geometry of the nozzle exit, the density of the gas, the heating value of the gas, the extent of assisted air mixing by steam injection or forced draft air, and the crosswind. Some correlations for entrainment of air by simple jets are available and will be discussed in Section 2.5.2.

TABLE 2-15. EXPERIMENTAL MEASUREMENTS ON FLARES

							MEASUREMENTS											
Author	Nozzle Size In	Fuel	Nozzle Velocity Ft/Sec	Firing Rate MBTU/Hr	Wind Mph	Steam lb/Hr	Axial	Radial	Flame Length Ft	CO_2	HC	CO	Soot	NO	O_2	Temp	Velocity	Eff. %
Lee & Whipple (1981)	0.125	C_3H_8	NR	NR	None	NO	√	NR[a]	NR	NR	√	NR	NR	NR	NR	NR	NR	NR
Lee & Whipple (1981)	2.0	C_3H_8	1.8	0.36	Calm	NO	√	√	5	√	√	√	NO	√	√	NO	NO	96-100
Palmer (1972)	0.5	C_2H_4	50-250	0.4-2.1	None	18-90	NO	NO	2-5	NO	√	NO	NO	NO	NO	NO	Calc.	>97.8
Siegel (1980)	27.6	Refinery[b] Gas	Variable	49-178	~15	290-6400	√	√	13-32	√	√	√	√	√	√	√	√	97->99
Howes (1981)	6	C_3H_8	40-60	44	13-17	(1)	√	√	20	√	√	√	√	√	√	√	NO	92-100
Howes (1981)	3x4"	CH_4	80	84	8	(2)	NO	NO	NR	√	√	√	√	√	√	√	NO	≥99.9

(1) Air Assisted

(2) High Pressure

[a] Not Reported

[b] 45-69 percent Hydrogen, balance C_1-C_4 hydrocarbons (Table 2.3)

The characteristics of the flame depend both on fuel and operating conditions, and considerable work has been carried out to define flame length, spread angle, and entrainment rate as a function of these variables. However, very little work is available on the movement of the flame, and the formation and transport of eddies.

Flame lengths have been defined in several ways, visible flame length being the most common. However, it does not represent the end of chemical reactions which may continue beyond the visible flame envelope. Therefore, a more precise definition of flame length is required and should ideally be defined as the point where the oxidation of the fuel and intermediates stop. However, in the experiments described later, flame length usually refers to the visible flame envelope.

Unburned fuel, partially oxidized fuel, cracked and polymerized products, and soot may all potentially be emitted from flares. All are products of incomplete combustion. The extent of incomplete combustion depends largely on the rate and extent of fuel-air mixing and the flame temperature achieved and maintained.

Jet diffusion flames are not steady state processes. The flame structure moves around as a result of combustion reactions, buoyancy forces, and combustion induced turbulence. Eddies are formed in the shear layers of the flame and may break away from the main body. In some instances a flame eddy may be quenched below the reaction temperature and extinguished. This can then result in the production of incompletely burned material which escapes as pollutants.

2.4.2 Characteristics of Previous Experimental Studies on Flares

A number of previous studies have contributed to the current state of knowledge of flare flames. This section reviews the experimental flare systems and operating conditions used in the previous studies.

Siegel (1980) made the only comprehensive study of a commercial flare system. He studied burning of refinery gas on a commercial flare head (type FS-6-anti-pollutant) manufactured by Flaregas Co. Table 2-3 shows the compositions of the flare gases used which consisted primarily of hydrogen (45.4 to 69.3 percent by volume) and the light paraffins (methane to butane).

Traces of H_2S were also present in some runs. The flare was operated from 0.13 to 2.9 metric tons/hour (287 to 6393 lb/hr). Hence, the maximum heat release rate was approximately 235 x 10^6 Btu/hr. However, most of the experiments were conducted between 49 x 10^6 and 178 x 10^6 Btu/hr.

Palmer (1972) experimented with a one-half inch ID flare head, the tip of which was located four feet from the ground. Ethylene was flared at 50 to 250 ft/sec at the exit (0.4 x 10^6 to 2.1 x 10^6 Btu/hr). Helium was added to the ethylene as a tracer at 1 to 3 volume percent and the effect of steam injection was investigated in some experiments.

Lee and Whipple (1981) studied a bench-scale propane flare. The flare head was two inches in diameter with one 13/16 inch center hole surrounded by two rings of sixteen 1/8-inch holes, and two rings of sixteen 3/16-inch holes. This configuration had an open area of 57.1 percent. One hundred and thirty-one (131) CFH of propane, doped with 12 CFH of helium, was fired through the flare head. The velocity through the head was approximately 3 ft/sec, and the heating rate was 0.3 MBtu/hr. The effects of steam and crosswind were not investigated in this study.

Howes, et al, studied flares produced on two types of commercial flare heads at John Zink's test facility. The commercial flare heads were an LH air assisted head and an LRGO (Linear Relief Gas Oxidizer) head manufactured by John Zink Co. Since both designs are proprietary, detailed configurations of the flare heads are unavailable. The LH flare burned 2300 lb/hr of commercial propane on a 6-inch diameter gas pipe. The exit gas velocity based on the pipe diameter was 27 ft/sec without air assist and the firing rate was 44 x 10^6 Btu/hr with air assist, and the combined velocity ranged from 40 to 60 ft/sec. The LRGO flare consisted of three burner heads 3 feet apart. The combined three burners fired 4200 lbs/hr of natural gas. This corresponds to a firing rate of 83.7 x 10^6 Btu/hr. Steam was not used for either flare, but the LH flare head was in some trials assisted by a forced draft fan.

2.4.3 The Structure of Flare Flames

Destruction efficiency and pollutant formation in flares is dependent upon their structure. In many previous studies, physical structure was often used to characterize flare flames. However, these studies were interested only in the gross properties of the flame, e.g., flame length, flame spread, and the rate of air entrainment. Although these properties are important, a more complete characterization is required if the mechanisms of pollutant formation are to be understood and emissions from flares assessed accurately.

An accurate characterization of flare flames requires a knowledge of the spatial distribution of temperature, velocity, and species concentration. The time-averaged value of these parameters is affected by the turbulent flame structure since their instantaneous values fluctuate with time. The instantaneous temperature profile influences the rate of destruction of material at any position in the flame. The concentration profile defines the local average species concentrations, the average rate of destruction or production of species, and the geometric limits of burning. The instantaneous velocity profile describes the flowrate and hence the flux of material in the flame. While some previous investigators have studied the temperature, concentration and velocity profiles in flares, most studies have concentrated only on visual observations of overall flame length, form and appearance. Observers report that the flare flame is typically not stationary, and that slight changes in, for example, the wind speed and direction can cause the flame to shift position and alter its shape. Many authors also report the presence of large coherent structures within such flames, where eddies develop along the length of flames and series of detached flame pockets results (Figure 2-7a). Eddies which are formed on the edges of the flame could be quenched and extinguished as a result of rapid heat transfer to the surroundings and thus be responsible for producing much of the incompletely burned fuel in flares. Yet the formation, separation, and quenching of eddies has been inadequately addressed in previous studies. However, some studies have recognized that quenched eddies could contribute significantly to emissions from flares. Gunther and Lenze (1972) have estimated that quenched eddies might result in as much as one percent of the fuel remaining unburned. Howes, et al, noted that more eddies were shed in high winds and that these eddies contained burning fuel. Lee and Whipple (1981) concluded that quenching of eddies was the major source of emissions from their flares. In contrast, Siegel identified eddies separating from his flare but concluded they were an unimportant source of emissions.

Figure 2-9 shows the potential emissions from incompletely combusted eddies as a function of the rate of eddy generation and efficiency of eddy combustion for the flare presented as an example in Section 2.3.1. For example, the inefficiency of the flame would be on the order of 1-5 percent if the eddy generation rate is 5-20 per second, and if the combustion efficiency is 50 percent. (These estimates are consistent with those made by Günther and Lenze, 1972.) These levels cannot be dismissed as small because even one percent inefficiency is significant when most studies have concluded that flares are greater than 99 percent efficient.

The amount of unburned material is predicted to increase as the diameter of the nozzle increases, provided the frequency of generation remains constant. However, the frequency of generation is probably smaller for a larger nozzle. Therefore, these effects of nozzle size are expected to cancel partially, but not completely. The effects of nozzle size will be discussed in more detail in Section 2.5.

2.4.3.1 Temperature Profiles in Flares

The spatial distribution of temperature in a flare flame is affected by wind, steam injection, and the heating value of the flared gas. With low wind velocities, the temperature profile in a plane above the flame appears to be normally distributed (Figure 2-10 and Siegel, 1980). However, recent evidence produced at Caltech (Dimotakis, 1981) indicates that the profiles in a turbulent flame are relatively flat except near the edges. The normal radial distribution of properties, usually measured in turbulent flames, is an artifact caused by fluctuations of the flame about the axis, i.e., the flame is present less frequently at large radial distances than at the center line. Consequently, the time-averaged temperature appears to decrease with increasing radius.

The time-averaged temperatures measured in such systems are not useful for making estimates of combustion rates. In many instances, the average measured temperatures are less than 600°C which is near the ignition temperature of most hydrocarbon fuels (Table 2-13). Hence, much of the fuel would be quenched before being burned completely if the average temperature were representative of the combustion process. However, these temperatures are not representative of the heat release zones, but rather the average tempera-

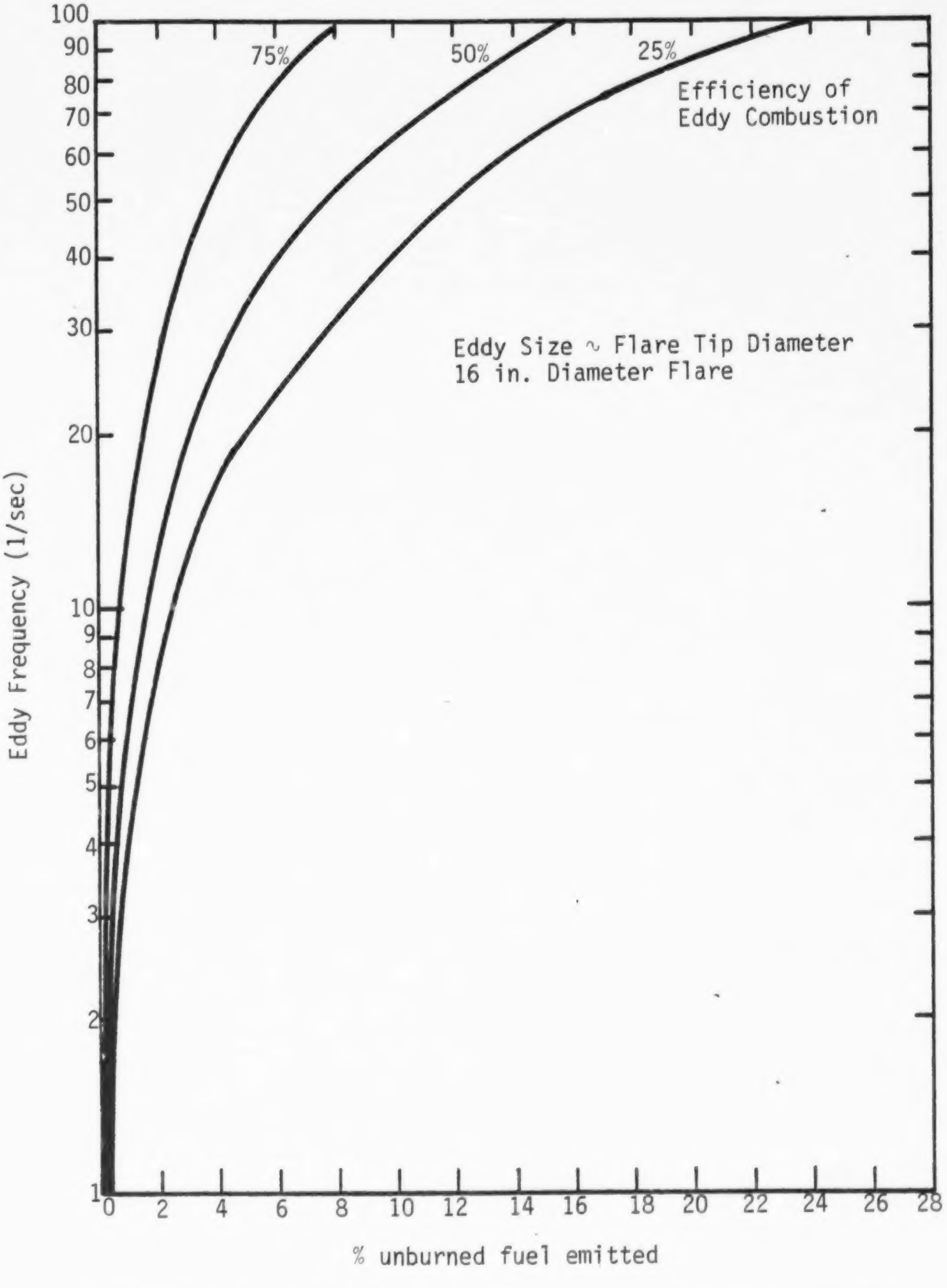


Figure 2-9. Estimates of flare emissions due to incomplete combustion of eddies.

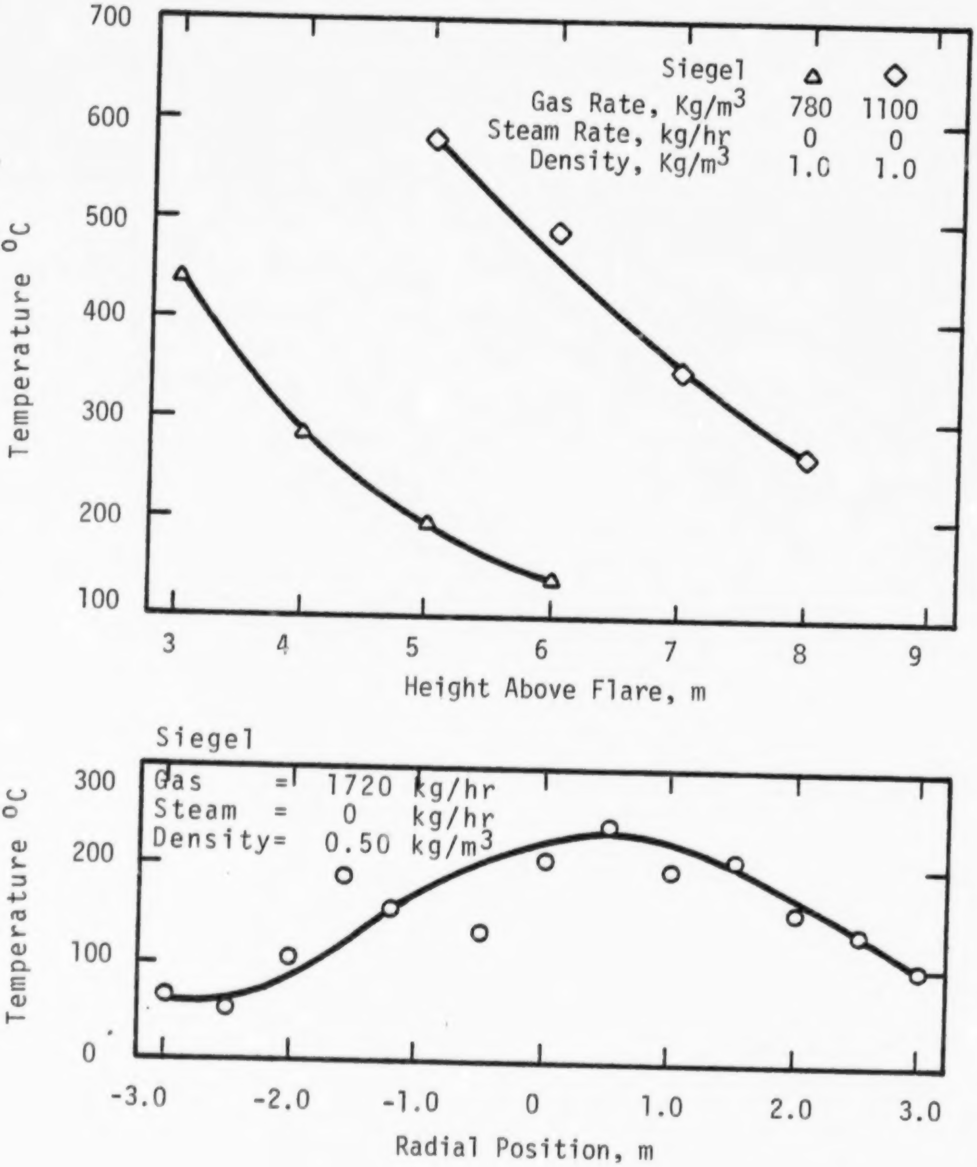


Figure 2-10. Temperature profiles in a commercial flare.

ture at a point where hot combusting eddies move through at some frequency followed by cold eddies. Thus, while the instantaneous temperatures of burning eddies can be used to predict combustion efficiency, the average measured temperature cannot.

The average measured temperature profiles in a flame help to define the boundary of combustion. Measured temperatures which approach ambient ones indicate that few hot eddies are passing the measuring location and, therefore, the location is outside the nominal edge of the flame. Axial temperature profiles in Figure 2-10 for two different flowrates reported by Siegel (1980) indicate that increasing the flowrate lengthened the flame and raised the temperature at the same distance above the nozzle. The radial temperature profiles show that at a position of 6.5 meters above a nozzle firing 3800 lb/hr of fuel the flame is approximately 6 meters wide. This flame is much wider than predicted by jet theory. However, Siegel used a divergent flare head which would induce more rapid spread of the jet than a normal head. However, others (Lee and Whipple, 1980) who have used normal flare tips have also found more rapid spread of flare flames than predicted by jet theory.

2.4.3.2 Concentration Profiles in Flares

The major components in a flare flame are O_2, CO, CO_2, hydrocarbons, H_2O, and carbonaceous particulates (soot). Since the flare entrains ambient air along its flow path, the concentration of combustion products becomes increasingly dilute. Thus, low concentrations of incompletely burned fuel species are not necessarily indicative of an efficient flare. Rather, the efficiency of the flare is the product of the instantaneous concentration and the instantaneous mass flux summed over an envelope enclosing the flare. In addition, the values must be averaged over a sufficient time period to ensure that the emission rate does not vary with time. This has not been done in previous studies and is impossible if conventional sampling techniques are used.

The measured normal distribution of concentrations in a flare flame appear to be the result of flame fluctuations. However, the averaged concentration profiles of the flame are more valuable than the average temperature profiles. The average concentration profiles can be used to calculate local destruction efficiencies, identify the regions of average production or destruction of a species, specify the concentrations of incompletely burned species, as well as to indicate the flame envelope.

Concentration measurements in flare flames have been made by Palmer (1972), Siegel (1980), Lee and Whipple (1981), and Howes, et al (1981). Table 2-16 shows the species and concentrations measured in these studies. Palmer made only single-point measurements of helium and ethylene. For inlet helium concentrations of about 1 percent, the concentration of helium at the end of the flame was between 21 and 206 ppm. The measured range for hydrocarbons was from 0 to 104 ppm. Lee and Whipple measured CO, total hydrocarbons, propane, and helium concentrations in a propane flame doped with 8 percent helium. Between 50 and 81 inches above the flare nozzle, the concentration ranges of the species were: CO, 7 to 1000 ppm; total hydrocarbons, 0.3 to 270 (arbitrary scale); propane, 1 to 6000 ppm; helium, 130 to 2700 ppm.

Measurement of low concentrations of species does not ensure that emissions from flares are insignificant. The concentration of species escaping the flame are diluted by air and exit the flame region at high flowrates through a large area. Figure 2-11 estimates the relation between measured concentration of propane and efficiency at various dilution levels and Figure 2-12 estimates the effect for emissions of carbon monoxide. At the estimated dilution of 1000, 30 ppm propane or 10 ppm carbon monoxide represent a one percent loss of efficiency.

Siegel has taken sufficient data to show the variation in average concentration distributions with distance under no-wind conditions. Figure 2-13 shows the measured O_2, CO_2 and gaseous hydrocarbons along the flare axis for two firing rates. These concentrations conform to one's expectation. Fuel burnout is displaced downstream for the flare with the higher firing rate. For both throughputs, the concentration of fuel decreases more rapidly than the CO concentration which indicates that the concentration of fuel is decreasing by consumption as well as by dilution. However, the instrument used by Siegel to measure CO was not sufficiently sensitive to determine the CO concentrations to the required accuracy. Extrapolation of the fuel concentrations to zero yields a reasonable estimate of flame lengths. The 780 kg/hr flame is 6 meters long and the 1100 kg/hr flame is 8 meters long.

TABLE 2-16. RANGE OF CONCENTRATIONS MEASURED IN FLARES STUDIES

			CONCENTRATION PPM$_V$				
Author	Tracer ppm$_V$	HC ppm$_V$	CO ppm$_V$	C_3H_8 ppm$_V$	CO_2 %	O_2 %	Soot mg/m$_3$
Palmer	21-206	0-104	-	-	-	-	-
Lee & Whipple	130-2700	a	7-1000	1.5-6000	0.5-1.0	19.8-20.3	-
Siegel	-	0-1200	0-2000	-	0.5-3	16-20	23-81
Howes	-	0->1000	0-5000	0->1000	0.1-7.2	9.6-20	<0.1-18

a Used arbitrary scale

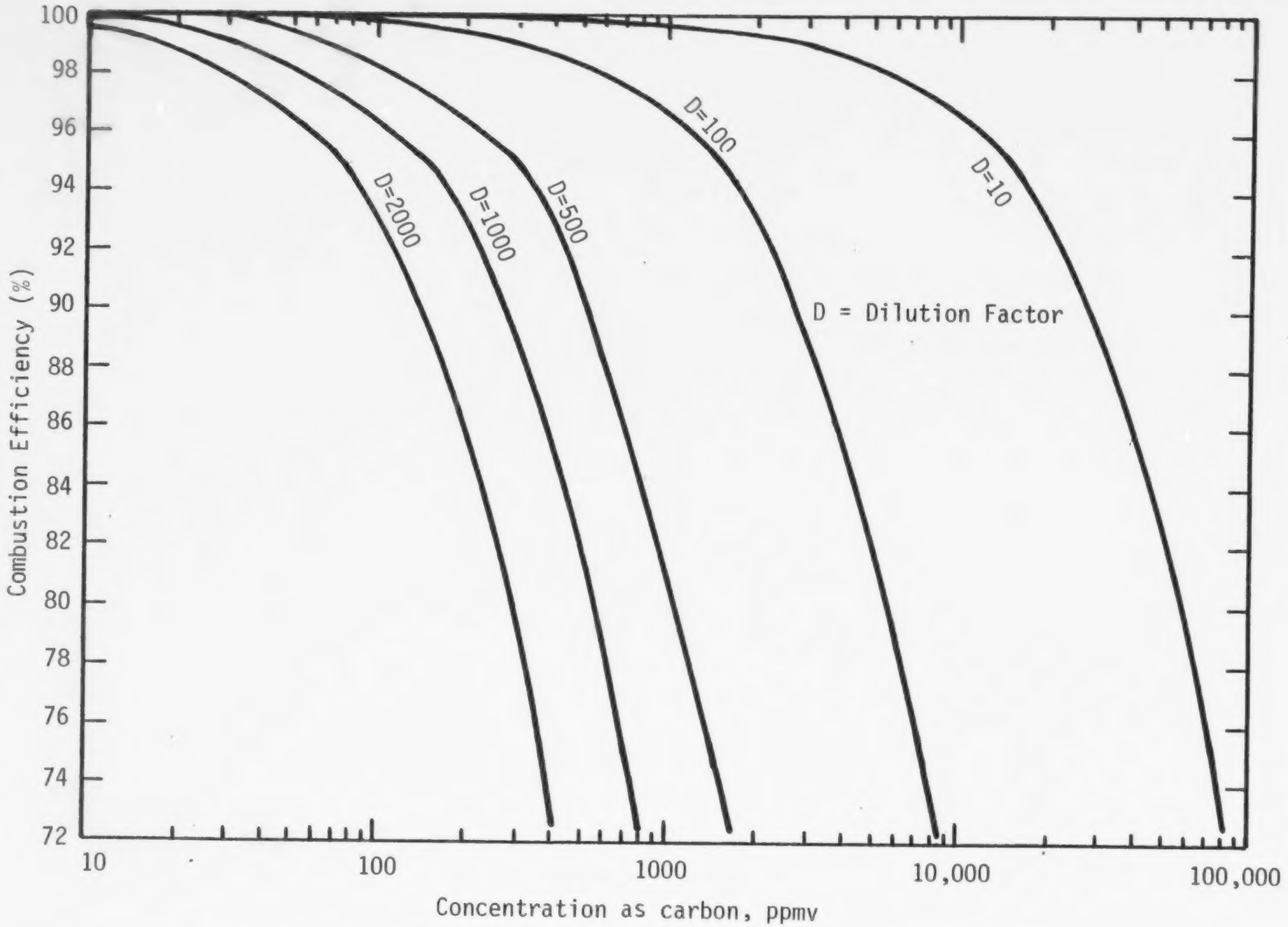


Figure 2-11. Effect of propane emissions on combustion efficiency. Propane as fuel.

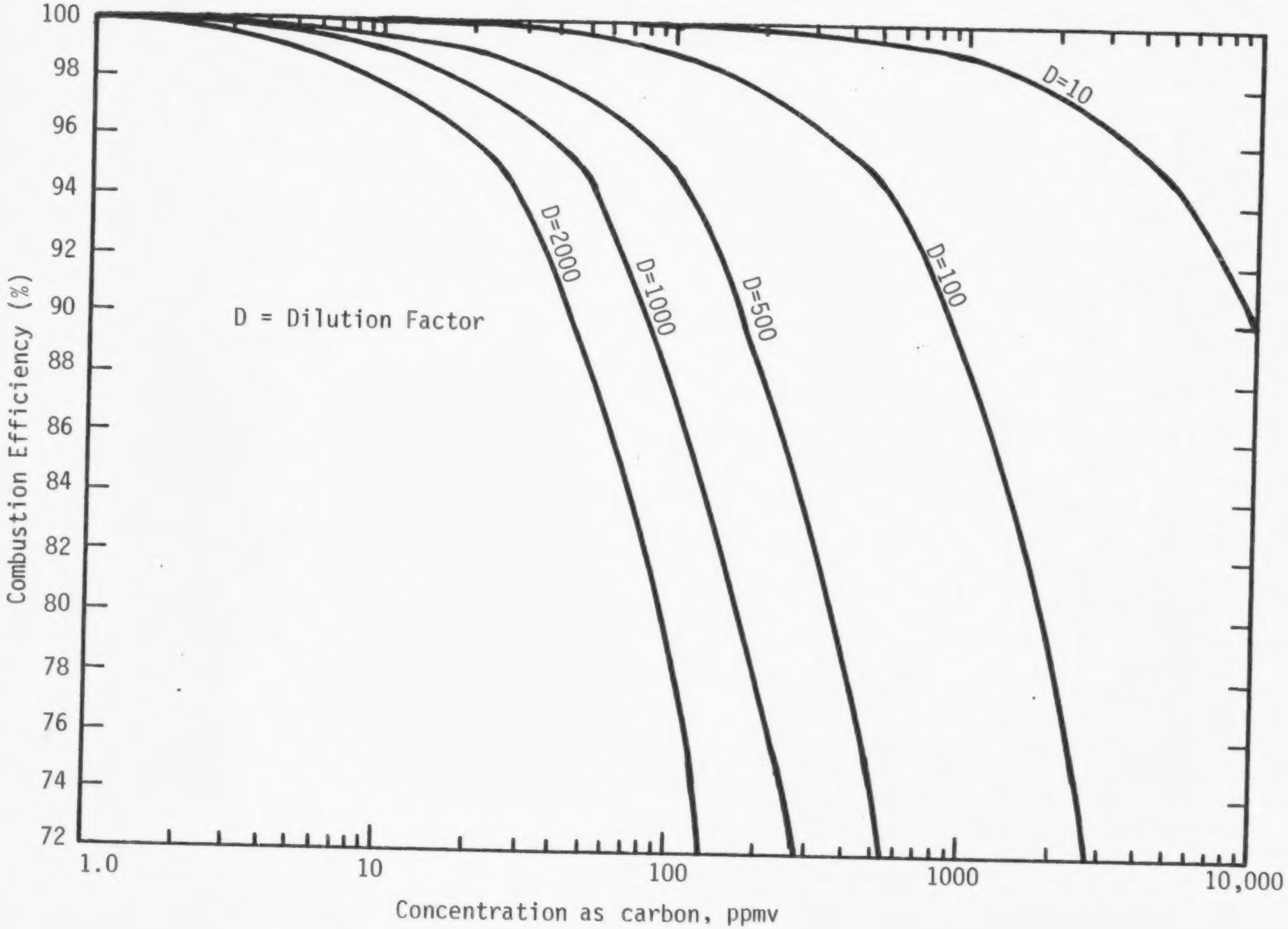


Figure 2-12. Effect of CO emissions on combustion efficiency. CO as fuel.

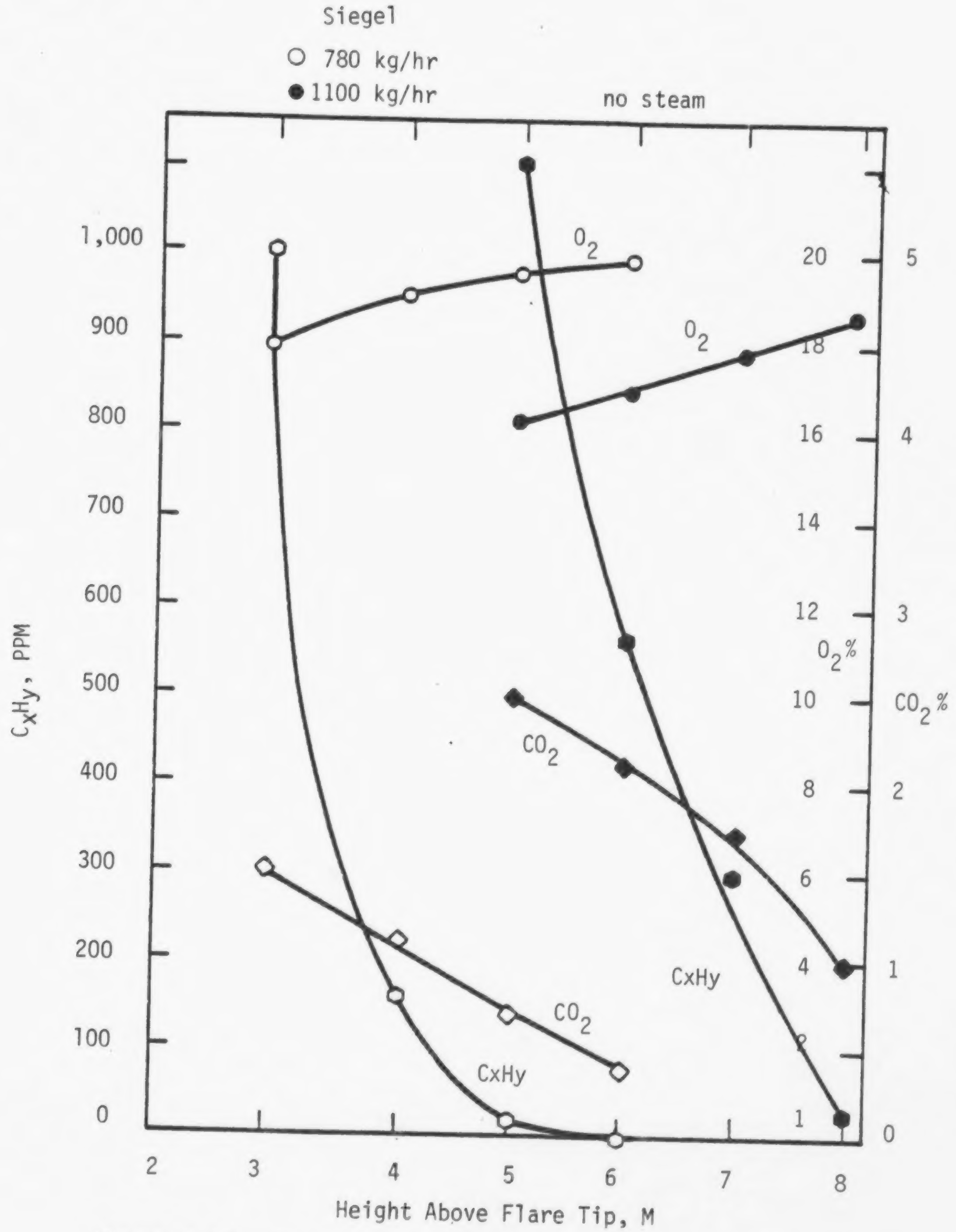


Figure 2-13. The effect of throughput on concentration profiles in two flare flames. (Siegel, 1980).

Radial profiles of concentration are also useful for defining the flame envelope. Profiles reported by Siegel (Figure 2-14) show some unusual characteristics. First, the profiles are asymmetric. The more rapid decrease of fuel, the larger concentration CO_2 and more gradual increase in O_2 concentration on the right side of the center line all indicate that on the average the flame burns more to the right than to the left side of the center line. This could be caused by distortion of the flare off-axis by the nozzle or wind, or by sampling for a time period which was insufficient to average the normal fluctuations. The concentration measurements also show considerable scatter on the left side of the center line which may be caused by intermittent shedding of eddies. Such phenomena are not accounted for in the sampling process.

Finally, fuel does not asymptotically approach zero concentration at the edges of the flame. Instead, the fuel concentration approaches an asymptotic value of 10 ppm. This concentration of fuel might contribute as much as 1 percent to flare inefficiency. In addition, the concentration of fuel should reach an asymptotic value of zero if transport of fuel occurred by diffusion alone. The finite asymptotic value implies that fuel is being transported from the center line by some mechanism in addition to diffusion. Once again, the most likely explanation is transport of fuel in large eddies that have broken away from the flame envelope, a phenomenon noted by Siegel, Howes, et al, and Lee and Whipple. Siegel concluded emission from quenched eddies was unimportant, while Whipple concluded that it was. Although the species concentration profiles of flare flames normally define the envelope of the heat release zone, interpretation of time-averaged profile concentration to produce flame envelopes is made difficult because of the fluctuating nature of buoyant turbulent flames.

2.4.4 Flare Efficiency

A major objective of many experiments on flares has been to determine their combustion efficiency. The efficiency of combustion is difficult to measure directly and, consequently, various methods have been proposed to provide pollutant emission indices for flares.

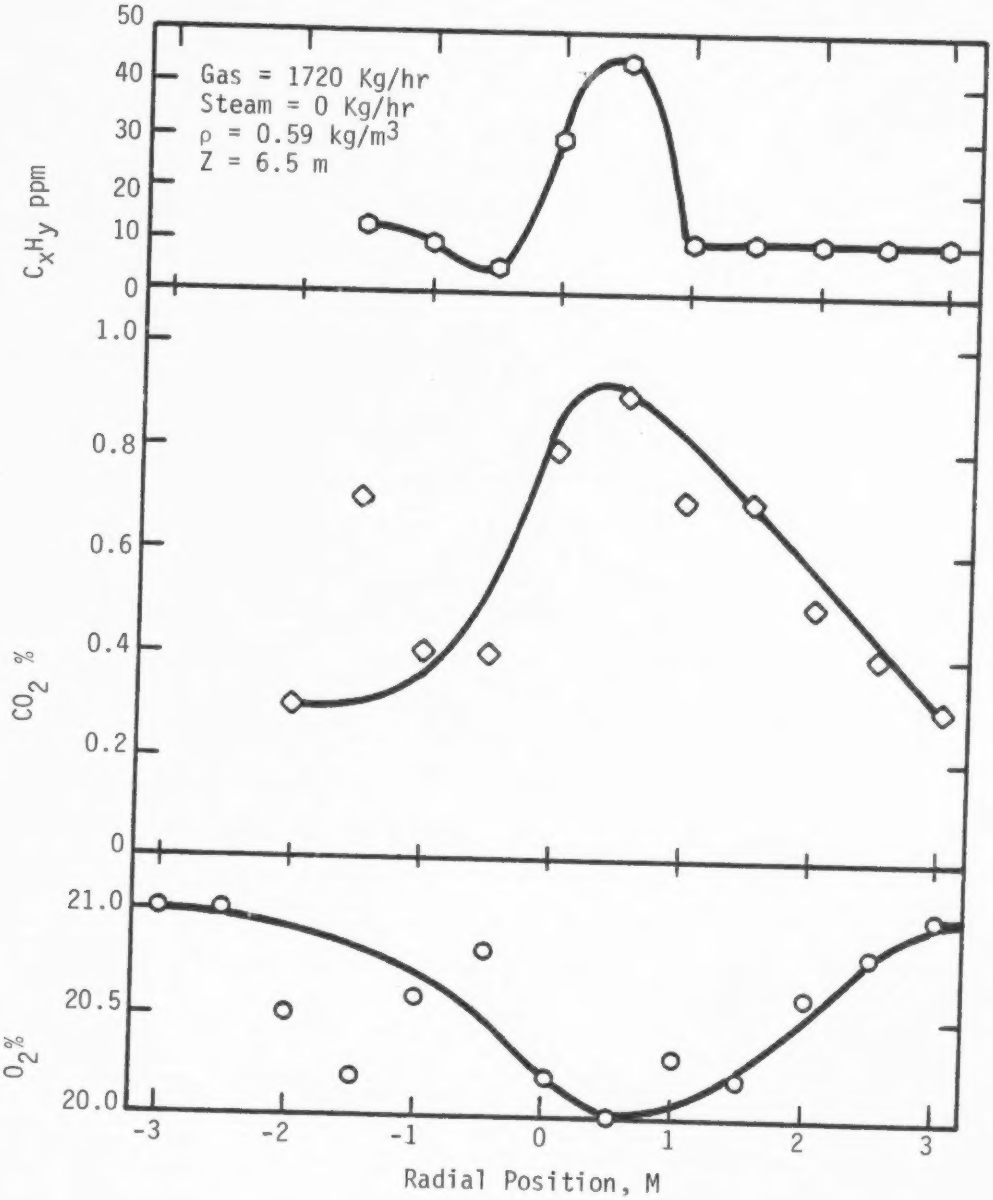


Figure 2-14. Radial concentration profiles in a flare flame. (Siegel, 1980).

Five methods have been used to calculate flare efficiency in previous studies (Table 2-17).

- Degree of carbon conversion (e.g., Siegel).
- Extent of destruction of flared gas (e.g., Lee, Palmer).
- Amounts of final combustion products formed.
- Emission of undesirable products/intermediates.
- Extent of the oxidation process.

In Siegel's study, efficiency was based upon local carbon conversion, U, defined in Table 2-17. This requires that measurements be made of the local gas velocity and concentration of all carbon containing species in order to specify an overall efficiency. Siegel attempted to close a material balance, but he was unable to account for approximately 50 percent of the input carbon. This was attributed to errors in the material balances caused by inaccuracies in the measured velocities. While inaccurately measured velocities can contribute to errors in the material balance, other factors must be considered, such as:

- Improper use of the average velocity and concentration.
- Errors in the average concentration caused by short sampling times.
- Incompletely burned material which escaped the flare undetected.
- Use of inappropriate techniques to integrate the mass fluxes.

Howes, et al, studied the measurement methods that may be applicable to flares. They determined species concentrations by analyzing samples withdrawn from the flame using a heated probe. The extracted samples were analyzed continuously for CO_2, CO, O_2 and THC. The probe was also used to extract grab samples which were analyzed by a modified SASS train for particulates and organic molecules.

Howes, et al, reported local destruction efficiencies between 92 and 100 percent, measured 2 m above the flame. The lower values were for sooting flares, and the higher values were for flares which suppressed soot. The study did not: (a) report global efficiencies, nor (b) confirm the accuracy of local efficiencies by different techniques.

TABLE 2-17. EXPERIMENTAL MEASURES OF COMBUSTION EFFICIENCY

1. Used by Siegel (global)

$$U = \frac{\dot{m}_c^{in}\left(C_mH_n\right) - \dot{m}_c^{out}\left(C_mH_n, CO, Soot\right)}{\dot{m}_c^{in}\left(C_mH_n\right)} .$$

2. Used by Lee (local)

$$DE = \left[1 - \frac{\left[C_3H_8\right] \times DF}{\left[C_3H_8\right]_o}\right] \times 100$$

where

$$DF = \frac{[He] \text{ in sample}}{[He] \text{ in flare gas}} .$$

3. Used by Palmer (local)

$$DE = \left[1 - \frac{\left[C_2H_4\right] \times DF}{\left[C_2H_4\right]_o}\right] \times 100$$

where

$$DF = \left(\frac{[He] \text{ in sample}}{[He] \text{ assuming 75\% reaction}}\right) \frac{1}{3.25} .$$

4. Used by Howes (local)

$$DE = \frac{M_c^{CO_2}}{M_c^{CO_2} + M_c^{CO} + M_c^{HC}} = \frac{\left[CO_2\right]}{\left[CO_2\right] + [CO] + [HC]}$$

where [HC] is the concentration of hydrocarbons as methane.

5. Proposed: (global)

$$DE = 1 - \frac{\dot{m}_{uhc}^{out}}{\dot{m}_{uhc}^{in}}$$

6. Proposed: (global)

$$F = \frac{\dot{m}^{out} \text{ of final products}}{\dot{m}^{out} \text{ assuming 100\% conversion}} .$$

7. Proposed: (global)

$$E = \frac{\Sigma\dot{m}_c^{out} \text{ undesirable species}}{\dot{m}_c^{in}} .$$

8. Proposed: (global)

$$O = \frac{O_2 \text{ consumed}}{\text{Theoretical } O_2 \text{ required for 100\% conversion}}$$

TABLE 2-17. EXPERIMENTAL MEASURES OF COMBUSTION EFFICIENCY (CONCLUDED)

9. Proposed: (local)

$$\alpha = \frac{12K_T \left[CO_2\right]_{ppm}}{\left[T\right]_{ppm} M_T} , \quad K_T = \frac{\text{Grams tracer in feed}}{\text{Grams carbon in feed}} .$$

10. Proposed: (local)

$$\eta = 1 - \frac{\left(36\left[C_3H_8\right]_{ppm} + 12\left[CO\right]_{ppm} + \left(\frac{RT}{P\tilde{N}}\right) m_c^{soot}\right) K_T}{\left[T\right]_{ppm} M_T}$$

where $RT/P\tilde{N}$ converts to volume units. m_c^{soot} is grams soot in sample.

11. Proposed:

$$\alpha' = \frac{m_c^{CO_2}}{m_c^{CO_2} + m_c^{uhc} + m_c^{co} + m_c^{soot}} =$$

where m_c denotes carbon from that species. Note that if $m_c^{soot} \approx 0$,

then $\alpha' \rightarrow$ Howes' DE (#④)

12. Proposed: (local)

$$\eta' = 1 - \frac{m_c^{uhc} + m_c^{CO} + m_c^{soot}}{m_c^{CO_2} + m_c^{CO} + m_c^{uhc} + m_c^{soot}} .$$

COMMENTS:

(a) Equations (2) and (3) are incorrect because they relate to propane and ethylene destruction efficiency only, and not to overall combustion efficiency. Soot, CO and lower hydrocarbons may also be present as uncombusted species.

(b) Equation (4) is subject to experimental error.

(c) Equations (5) - (8) are unworkable in current format without a hood, as is Equation (1)

(d) Equations (11) and (12) rely on assumed mass balance.

SUGGESTIONS:

(a) Use Eq. (9) until mass balance is obtained, then use Eq. (10) to quantify local efficiencies.

(b) Given local efficiencies, weight them according to area and velocity to give global efficiency and check this result with that obtained by using the hood and Eq. (1) or (7).

Palmer (1972) measured the local efficiency of an ethylene flare. His data are tabulated in Table 2-16. Palmer withdrew grab samples into 2.25 liter bags with a probe from a position two feet downstream of the "flame tip.: The samples were analyzed for helium (used as a tracer) by gas chromatography and mass spectrometry and for ethylene (fuel) by gas chromatography and flame ionization detection.

The helium tracer technique used by Palmer to obtain local combustion efficiency is questionable. Helium is a poor tracer because the diffusion velocity is much higher than the major components in the flare. Consequently, helium will diffuse more rapidly away from the flame region and produce dilution factors that are erroneously high. The sampling time used by Palmer, one minute, is probably insufficient to accurately determine the species concentrations of a fluctuating flame. In addition, Palmer sampled only on the axis and did not attempt to sample or integrate the concentrations to obtain a global combustion efficiency. The sampling system used by Palmer could not accurately determine the concentration of high-boiling-point hydrocarbons which were observed. Also, the helium analyses, which were the basis for the mass balance calculations, were only accurate to ± 6.7 percent. Consequently, Palmer's data are of limited value in assessing the emission of incompletely burned material from flares.

Lee and Whipple (1981) have also reported local efficiencies measured on a pilot-scale flare using a helium tracer to determine dilution factors. Destruction profiles of propane, hydrocarbons, and carbon monoxide are shown in Figure 2-15. Although no soot concentration measurements were attempted, the data can be utilized to determine minimum carbon emissions by considering the sum of propane and CO only (Figure 2-16). They also reported combustion efficiency of 96 to 100 percent. However, the data contained the same potential errors as the other data on flares. Only local concentrations were determined. The tracer used will potentially yield too high a dilution factor because of the high diffusivity. The sampling time was 5-10 minutes, but as will be shown later, still too short to achieve the accuracy required. It should be noted that escape of 0.001 percent of the fuel represents about a one percent loss in efficiency, and this was ignored.

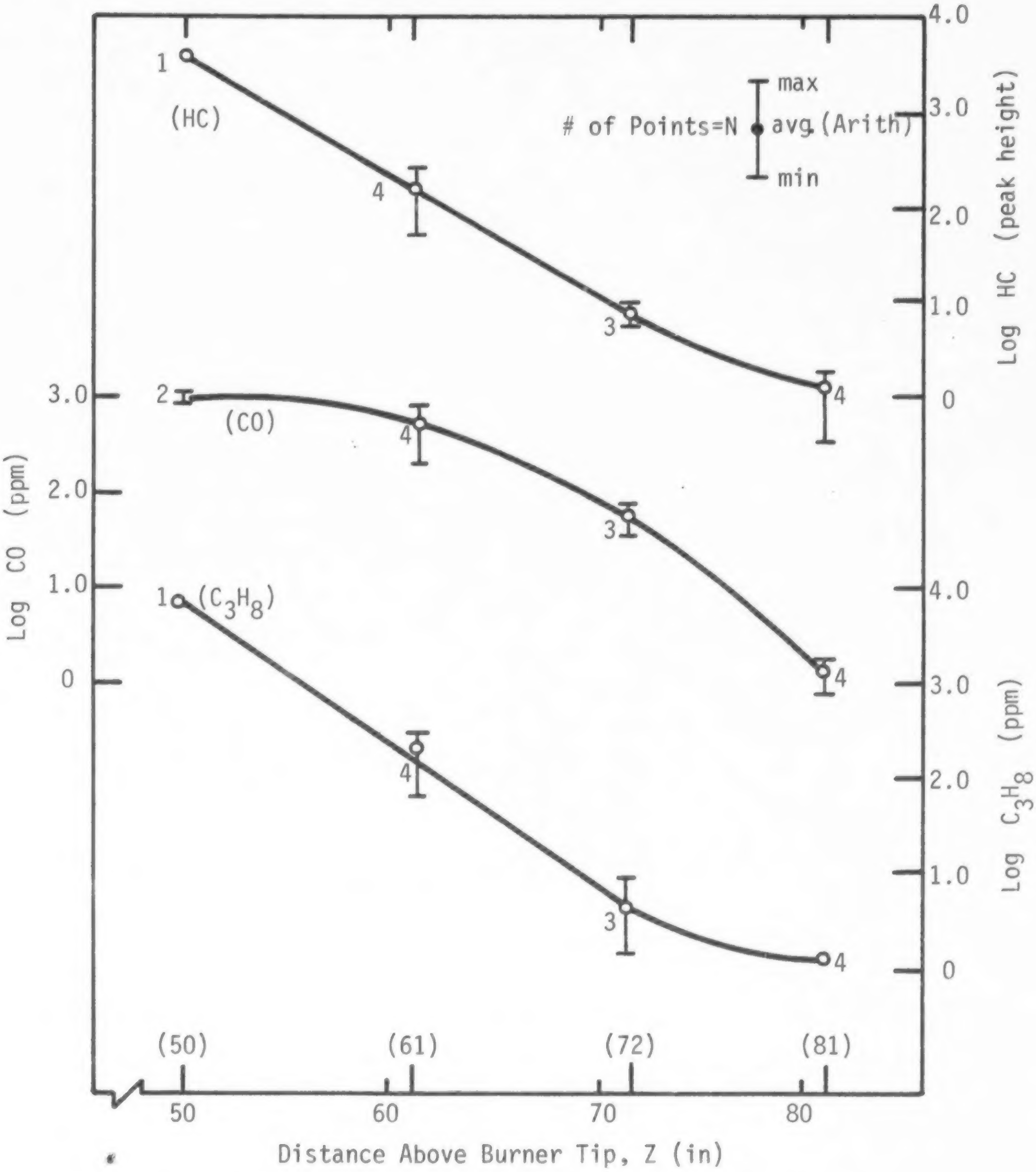


Figure 2-15. Species centerline concentrations as a function of height above burner. Fuel 92 percent propane, remainder helium tracer. Calm wind, sooty flame. Effective nozzle diameter 1.51 in. (Lee and Whipple, 1981).

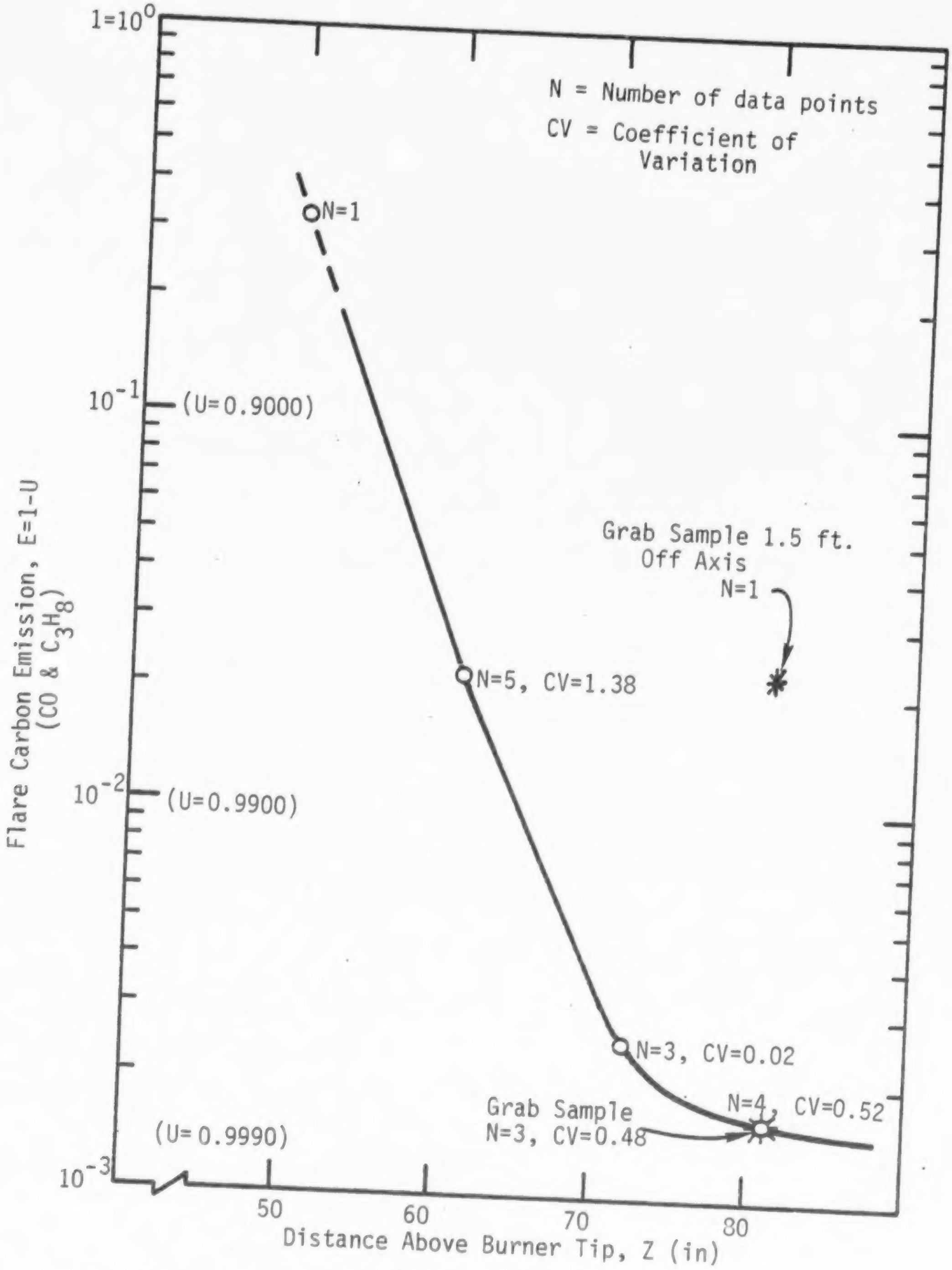


Figure 2-16. Summary of flare emission, excluding soot, as a function of height above burner tip. Same conditions as Figure 2-15. (Lee & Whipple, 1980).

Concentration of species has been measured above and in flares. However, interpretation of these results is difficult because of the intermittent nature of flare flames. Estimates reveal that in order to determine the efficiency of a flare, concentrations must be measured down to about 10 ppm. Instruments used by Howes, et al, and Lee and Whipple were sensitive enough so that emissions could have been determined. However, instruments available to Siegel were not.

2.4.5 Production of Soot in Flares

The amount of soot produced in flares can materially affect the flare efficiency. Figure 2-17 shows that a concentration of 15 mg/m^3 of soot at a dilution factor of 1000 corresponds to a loss of one percent in flare efficiency. However, few studies have measured the concentration of soot. This is so partly because the measurements are time consuming. Sometimes, soot measurements are considered unnecessary because some flares burn non-sooting fuels, while others inject steam or air to suppress soot formation during most operating conditions.

Howes, et al, and Siegel made limited soot concentration measurements. However, their measurements were neither systematic nor complete. Howes measured soot concentrations ranging from less than 0.1 mg/m^3 for natural gas flared on a LRGO head, to 18.3 mg/m^3 for C_3H_8 flared on an LH head. The efficiency loss caused by a soot concentration of 18.3 mg/m^3 at a dilution factor of 1000 is about 1.5 percent. Siegel measured soot concentration ranging from 20 to 80 mg/m^3 in a sooting flare. He estimated that production of this amount of soot resulted in an efficiency loss of 2 to 4 percent. Figure 2-17 would indicate an efficiency loss of about 1.5 to 5.5 percent at a dilution factor of 1000. The observed concentration of soot from flare flames can, therefore, substantially alter combustion efficiency. The concentration of soot should be measured in future studies to levels below 10 mg/m^3.

2.4.6 The Effect of Wind on the Performance of Flares

Elevated flares are exposed to uncertain weather conditions including changes in wind velocities. In a calm atmosphere, the flare flame primarily fluctuates about the center line of the flare head. As the crosswind velocity

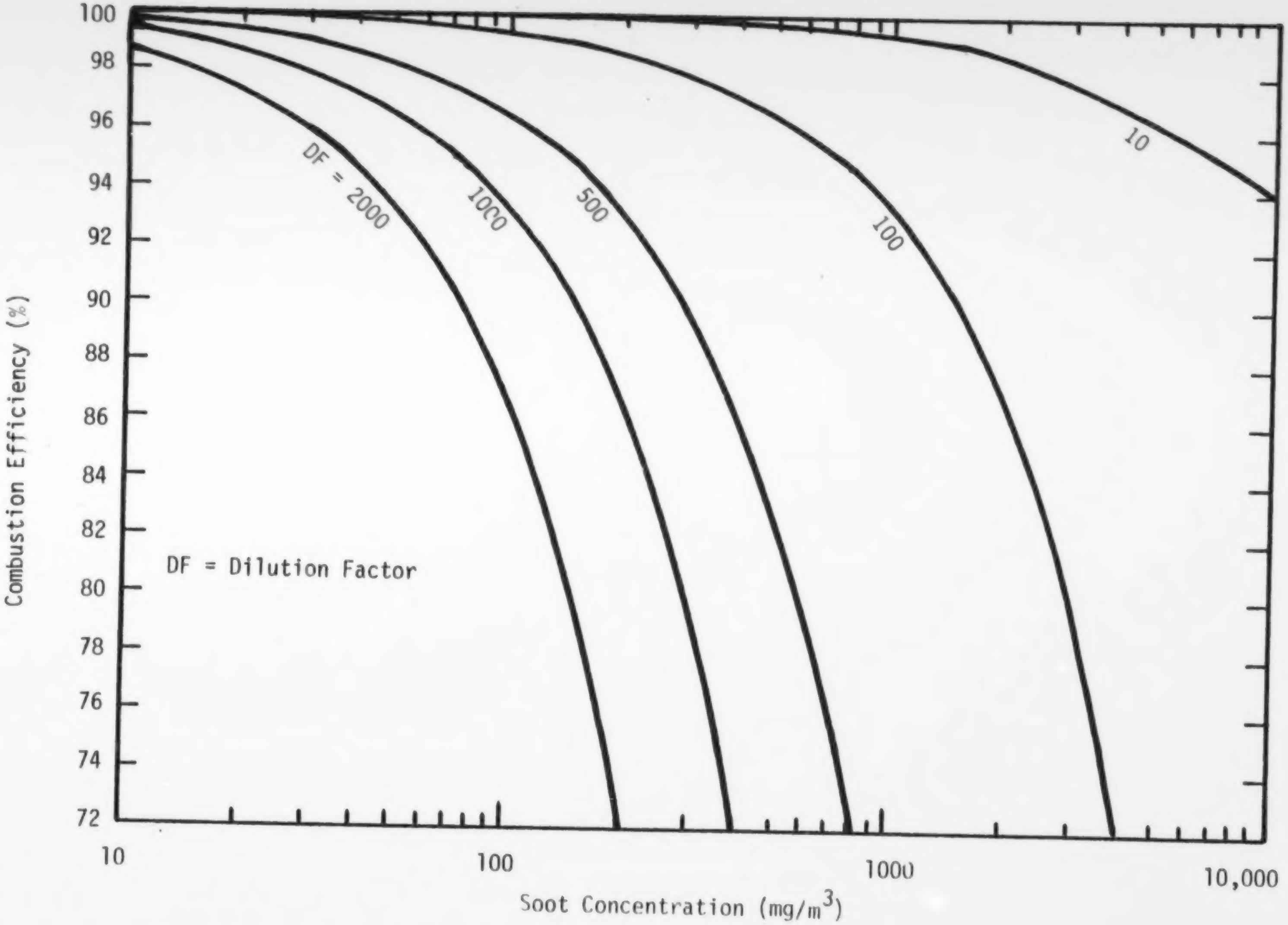


Figure 2-17. Effect of soot concentration on combustion efficiency. Propane as fuel.

increases, the flame axis is bent in the direction of the wind. As the wind promotes penetration of air into the flame, combustion is enhanced and the flame is shortened. When the wind velocity increases further, the wind velocity dominates and the flame becomes longer, and the possibility for stripping unburned material from the flame edges increases.

The effect of crosswind on the efficiency of flames was studied to a limited extent by both Siegel and Howes, et al. Howes, et al, studied flames subjected to winds from 8 to 17 mph, while Siegel studied flares subjected to winds up to 15 mph. A crosswind makes measurements and the closing of material balances in flames very difficult. Thus, reported measurements are of limited value.

Global efficiencies have not been measured for flares in the presence of wind, but some local efficiencies have been reported. For a flare in a 6.7 m/s wind, Siegel reports that local combustion efficiency on the center line of the flare approaches 97 percent, compared to better than 99 percent at a comparable point in quiescent conditions.

2.4.7 The Effect of Steam Injection/Forced Draft on the Performance of Flares

In practice several methods are used to reduce soot production and improve the efficiency and visual appearance of flares. These methods normally serve to improve air induction and mixing at the root of the flame. Air can be induced by the use of separate steam jets injected into the base of the flame, by aerodynamic means such as in the Coanda flare, by premixing, or by the use of forced draft fans. The induction of additional air into the flame typically increases combustion intensity, shortens the flame, and improves the efficiency.

Howes, et al, studied a John Zink LH flare which used a forced-draft fan to assist air mixing, and a John Zink LRGO flare which burned high pressure gas. The estimated local efficiency of the LRGO flare was slightly better than that of the LH flare. But since the LRGO flare burned methane and the LH flare burned propane, comparisons are difficult. In one case, Howes, et al, estimated the local efficiency of the LH flare without using the forced-draft fan. In this test, soot concentration increased by a factor of 20, and the estimated local efficiency dropped from greater than 99 percent to 92 percent. Use of forced-draft fans definitely improves the efficiency of flares. However, forced draft fans are impractical on the very large elevated flares which potentially can contribute significantly to the emissions of incompletely burned fuels from flares.

Induction of air through the injection of steam is the most common method of improving the efficiency of large elevated flares, and both Palmer and Siegel have studied the effect of steam injection into flares.

Palmer estimated the efficiency of a flare with and without injection of steam. He reported that the flame length did not strongly depend on exit gas velocities for velocities between 50 and 250 ft/sec. However, injection of steam changed the physical characteristics of the flame. Without steam injection, the flame was between four and one-half and five and one-half feet long, "lazy," reddish, and smoky. When 0.3 lbs of steam was injected for each pound of ethylene, the flame became turbulent, shortened to two feet and emitted no smoke.

Siegel studied the effect of steam injection on the performance of flares more systematically. He demonstrated that injection of steam changes the physical characteristics of the flare and that the changes are reflected in the concentration profiles of the flare and the local combustion efficiencies. An optimum level of steam injection exists, which depends on the characteristics of the gas being flared.

Steam injection changes the physical characteristics of the flare in a manner which suggests that the intensity of combustion is increased because the flame is shortened, its luminosity is reduced, and soot formation is suppressed. Figure 2-18 shows that the flames are shortened by about 50 percent at a steam/gas ratio of approximately 0.1. Without steam, the flame was very sooty. Steam injection changes the color of the flame from orange to yellow. When the steam/gas ratio reaches about 0.25, soot production was suppressed. At steam/gas ratios of about 0.55, the flame develops a blue inner cone and a yellow outer cone. When the steam/gas ratio was above 0.55, the blue inner region spread to the entire flame and it resembles a fully premixed flame. Increasing steam/gas ratio past 1.35 produces a white inner cone which contains steam and water.

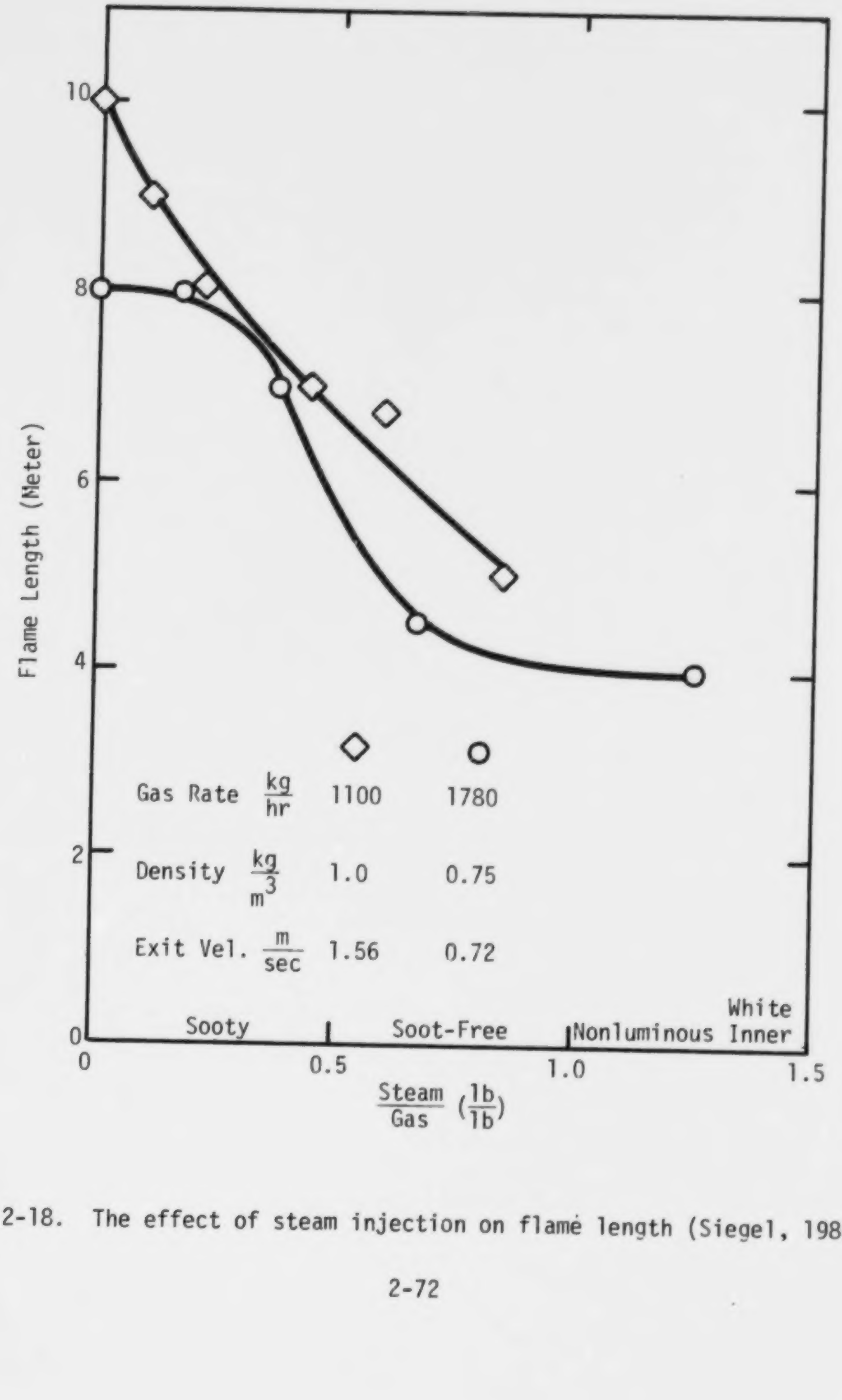


Figure 2-18. The effect of steam injection on flame length (Siegel, 1980).

The rate of decrease of the concentration of unburned hydrocarbon species in flares increases as more steam is injected until a limit is reached. Figure 2-19 shows the concentration profiles reported by Siegel as a function of the amount of steam injected. The incompletely burned fuel, C_xH_y and CO decrease rapidly as more steam is injected. For steam/gas ratios below 0.6, CO and C_xH_y were detected at 3 meters above the flare head, but not at 6 meters. Between ratios of 0.6 and 1.0, no C_xH_y could be detected at any level. Injection of steam into flares, therefore, also improves the local efficiency. Siegel calculated local efficiencies at two different locations. As the ratio of steam to gas is increased, the local efficiency increases (see Figure 2-20). For a steam-to-gas ratio greater than 0.7, local combustion efficiencies were estimated to be greater than 99.9 percent for both locations.

While some steam injection into the flare improves combustion efficiency, excessively high rates of steam injection can reduce combustion efficiency (Figure 2-19). At steam-to-gas ratios above 1.2, C_xH_y could be detected at three and six meters, suggesting that increasing steam actually reduced combustion efficiency. Injection of steam up to 0.9 pound of steam per pound of fuel, apparently increases the mixing of air and hence the intensity of combustion and the efficiency of the flare. High rates of steam injection induce more air, but the amount of air and steam injected at these high rates dilutes the combustibles and lowers the flame temperature. Figure 2-21 shows that temperatures at all heights in the flare reach a maximum temperature at about 0.9 pounds of steam per pound of fuel. Therefore, an optimum level of steam injection exists for this fuel.

Siegel has also shown that the optimum level of steam injection is different for different fuels. He reported that more steam was required to eliminate soot from denser fuels. For example, a gas with density of 1.1 kg/m^3 required a minimum steam/gas ratio of 0.20, while a gas with density of 1.86 kg/m^3 required a ratio of 0.37. Moreover, the degree of conversion for the two flames was better than 99 percent provided sufficient steam was injected for visually soot-free combustion. The density of the fuel controls mixing of air. However, based on the temperature effect, the effect of steam must also depend on the heating value of the fuel and possible fuel chemistry.

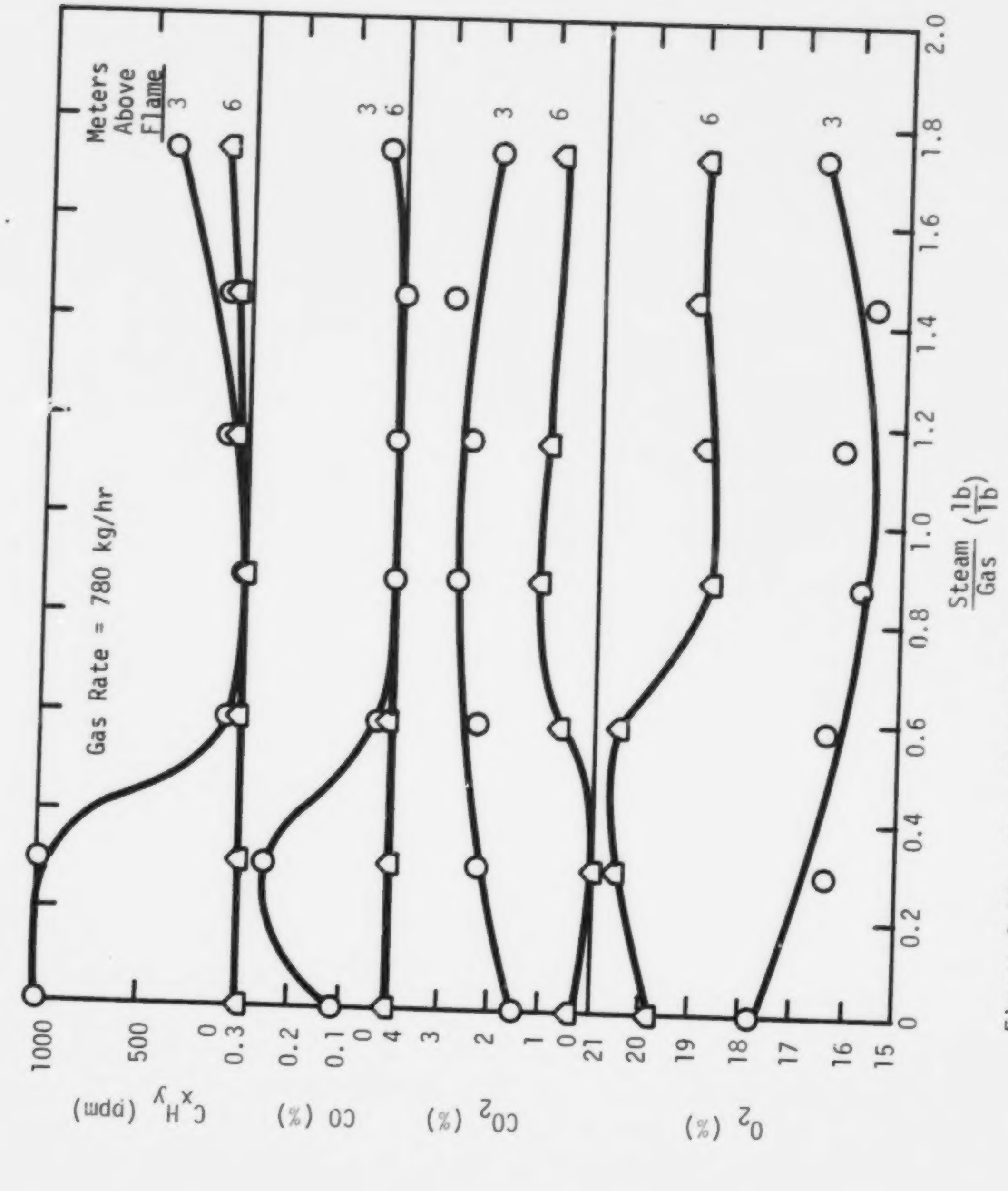


Figure 2-19. The effect of steam injection on concentration profiles, 3 and 6 meters above the flame tip (Siegel, 1980).

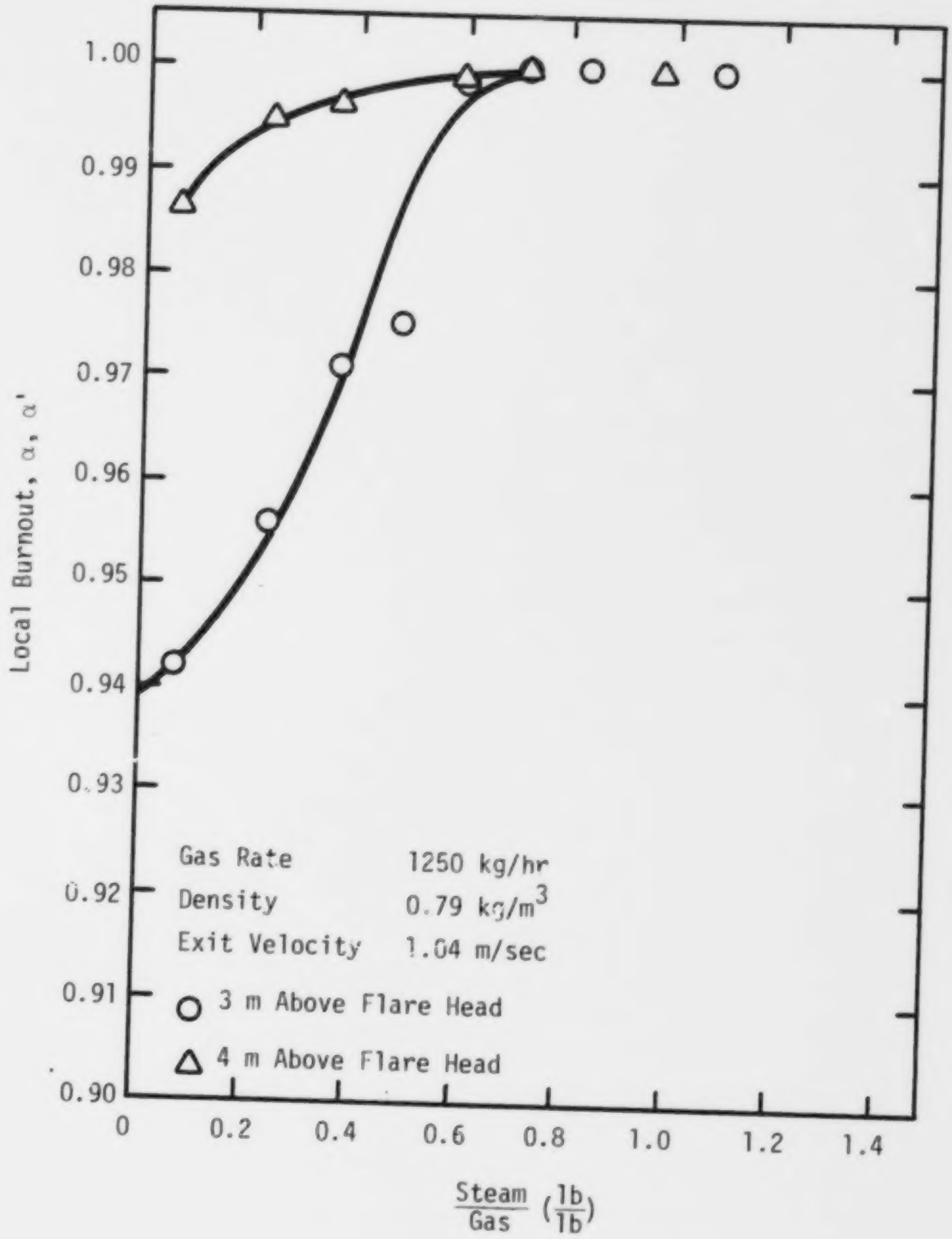


Figure 2-20. The effect of steam injection on local flare efficiency (Siegel, 1980).

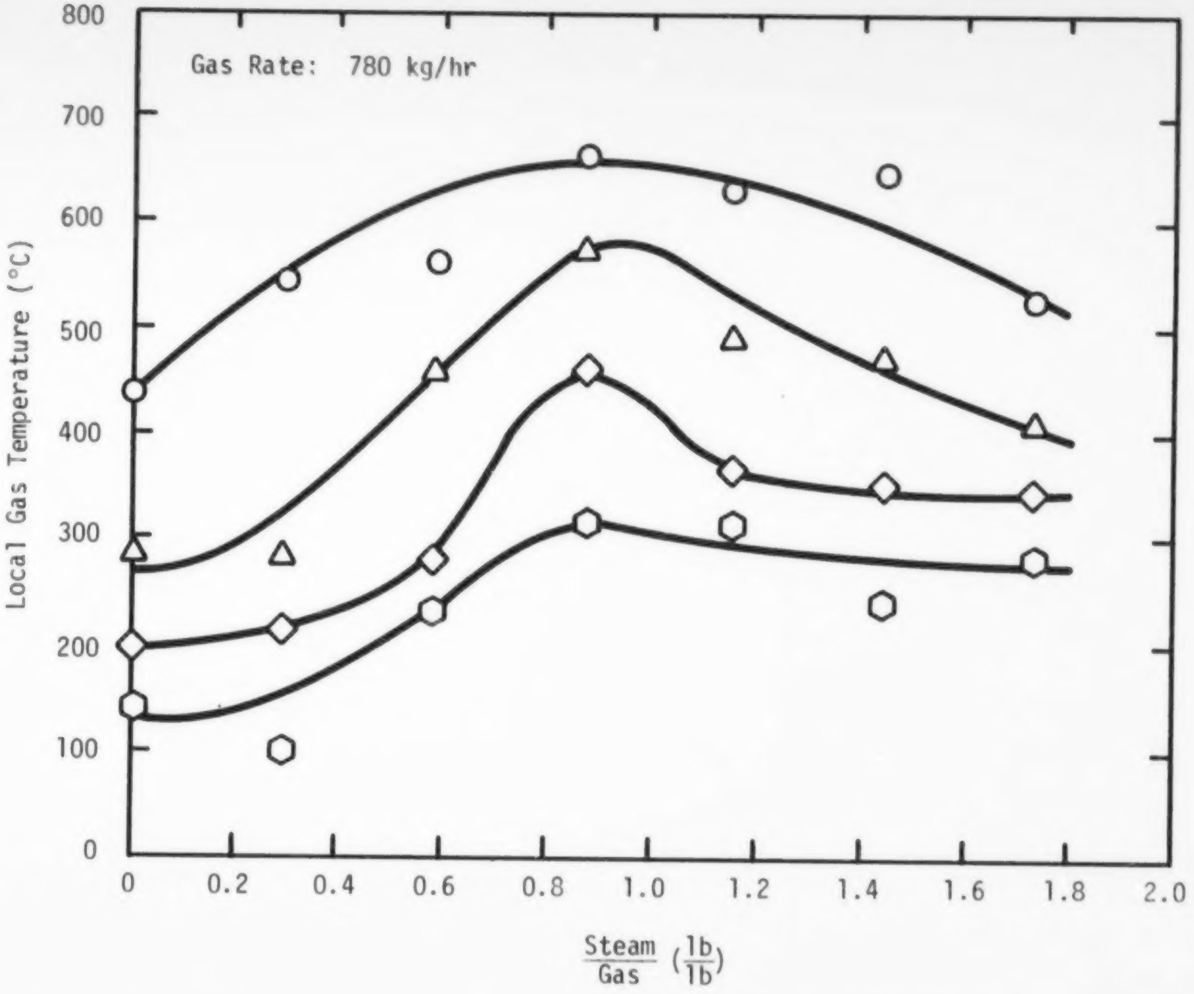


Figure 2-21. The effect of steam injection on temperature (Siegel, 1980).

Techniques used commercially to suppress soot and improve the efficiency of flares appear to be effective as designed. However, a better understanding of the mechanism of air induction into the flare will allow better control of the techniques and provide for the maximum reduction in operational costs.

Previous studies have contributed to our knowledge of the character of flare flames. However, these studies have been unable to quantitatively determine the emissions or structures of the flames. In addition, no scaling or modeling criteria were presented. Consequently, the data could not be properly interpreted and extrapolated to commercial systems. The following steps should be taken in future studies to avoid these problems:

1. Concentration of soot should be measured below 10 mg/m^3.
2. Concentrations of CO and hydrocarbon should be measured below 10 ppm.
3. The instantaneous values of concentration, density, and velocity should be simultaneously measured.
4. The effects of fuel on emissions from flares should be determined.
5. The effects of operating conditions on emissions from flares should be determined.
6. The effect of steam injection on the emissions from flares should be determined.

2.5 Modeling of Flares

A major objective of any future program on flares should be to develop information and methods which allow the performance of industrial flares to be estimated. To accomplish this economically, the program must measure emissions from representative small-scale flares and establish a rational method for scaling the results to full-size systems in order to develop emission factors for industrial flares.

Flare flames are basically vertical free turbulent diffusion flames, where the majority of the combustion process appears to occur at the surface of numerous separate coherent eddy flames. The efficiency of a flare is therefore more likely to be not only a function of size, but also of those factors which affect eddy formation and detached flame combustion. This concept of combustion in detached flames is supported by the experimental work described in preceding sections. The use of subscale experiments to optimize full-scale design requires, therefore, knowledge of fundamental physical and chemical mechanisms and a mathematical model of turbulent flames that quantifies the mechanisms.

Several models have been considered for use in a description of flare combustion. Early models of turbulent diffusion flames were found unsuitable because they only crudely predicted gross properties such as flame length and air entrainment and were not capable of estimating emissions. Computational solutions to the time-averaged Navier-Stokes equations by existing means is on the other hand expensive, and these solutions do not predict intermittent, turbulent quantities realistically. Since intermittency due to turbulent eddy breakaway and quenching appears to have a major effect on combustion efficiency, any model that ignores the phenomenon is incomplete and subject to error.

New approaches to scaling are being developed and are potentially capable of predicting gross structural properties, as well as emissions from flares. In addition, modification of more advanced but still simple models which are also currently being developed at the California Institute of Technology may be applicable to the prediction of flare emissions. More complicated models exist in the literature but are unable to account for the effects of large eddies or the intermittent production of emissions nor have they been experimentally ratified. These models will be difficult to modify to properly account for emissions from flares.

2.5.1 Models of Flare Behavior

A quantitative model of a flare flame must accurately describe the physical processes taking place around the flame. In normal operation, flares produce large, low-momentum, turbulent diffusion flames as in Figures 2-7 and 2-22. Shear stress and instabilities on the flame boundary produce large eddies that depart from the bulk flow as shown conceptually in Figure 2-23. Once detached, these eddies act independently from the bulk of the flame, engulfing ambient fluid, stretching, mixing internally, losing heat by convection, radiation, and subsequent quenching of the combustion reactions (Figure 2-24). Clearly, any realistic model of flares and flare emissions

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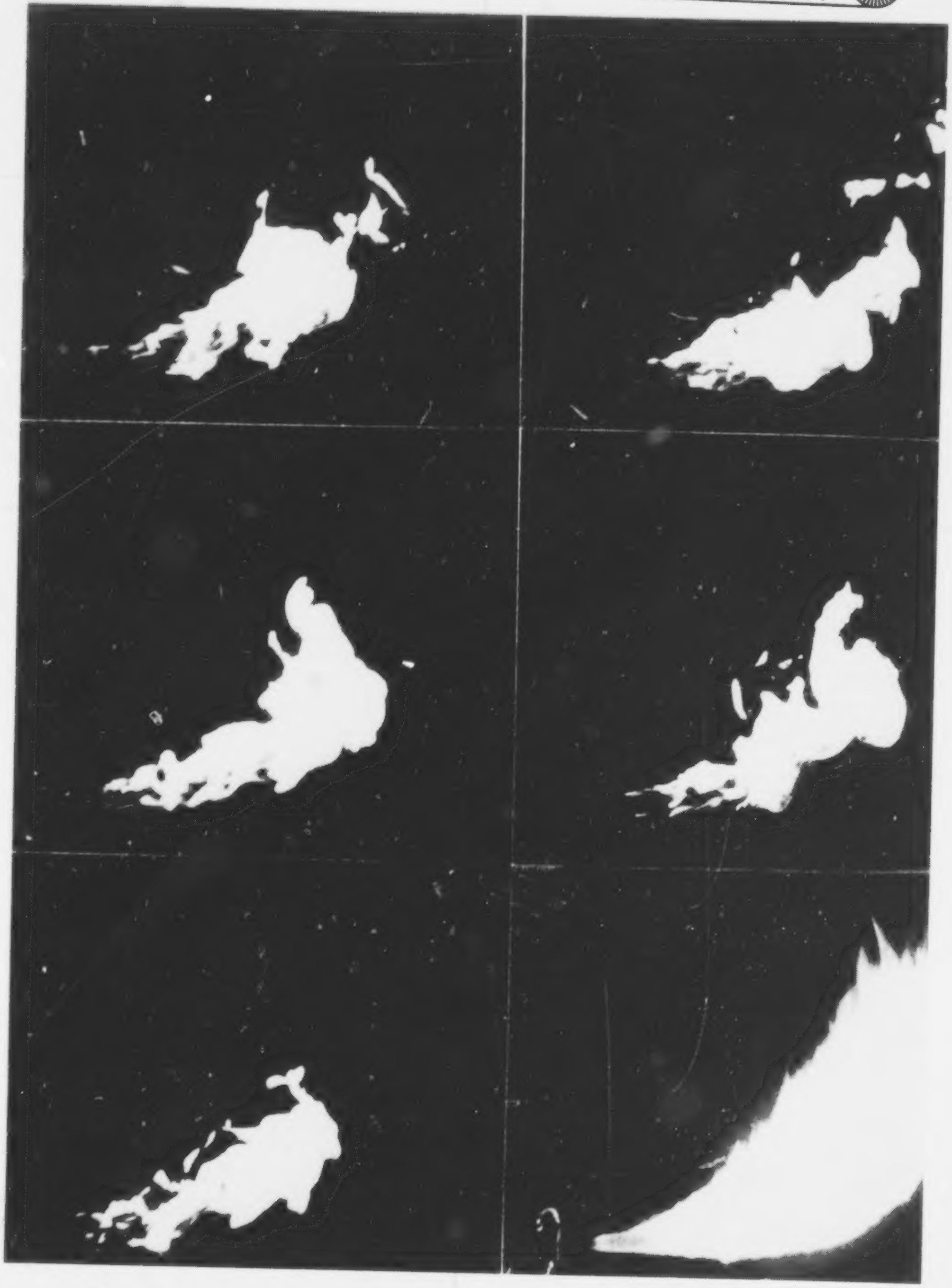

Figure 2-22. Short time photographs of turbulent flame. (Becker, et al, 1981. Reprinted with permission of The Combustion Institute.)

Eddy Formation

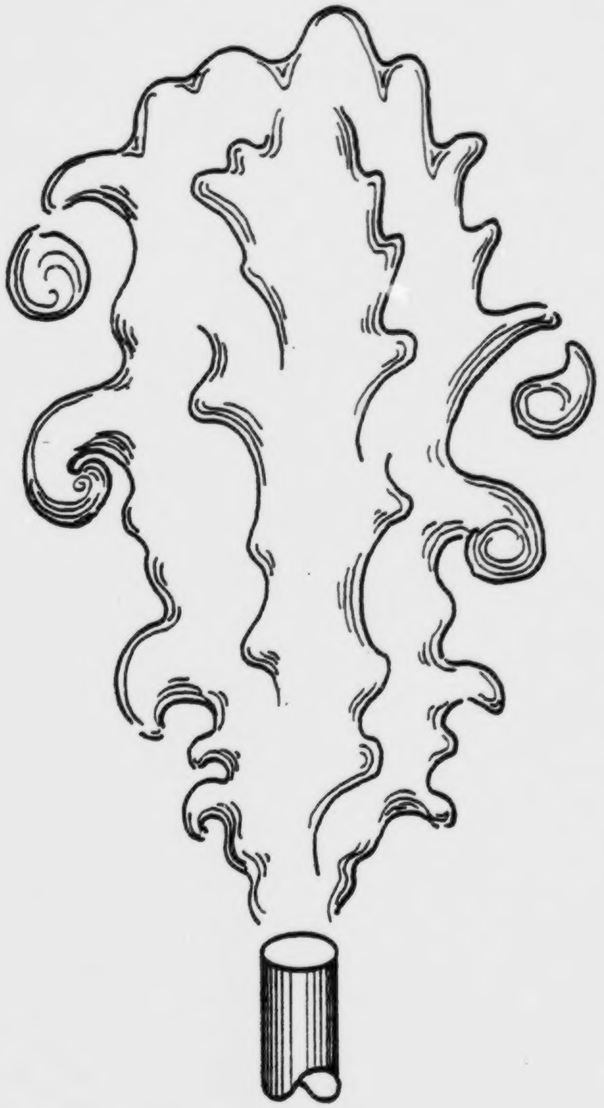

Figure 2-23. Conception of a flare shedding eddies.

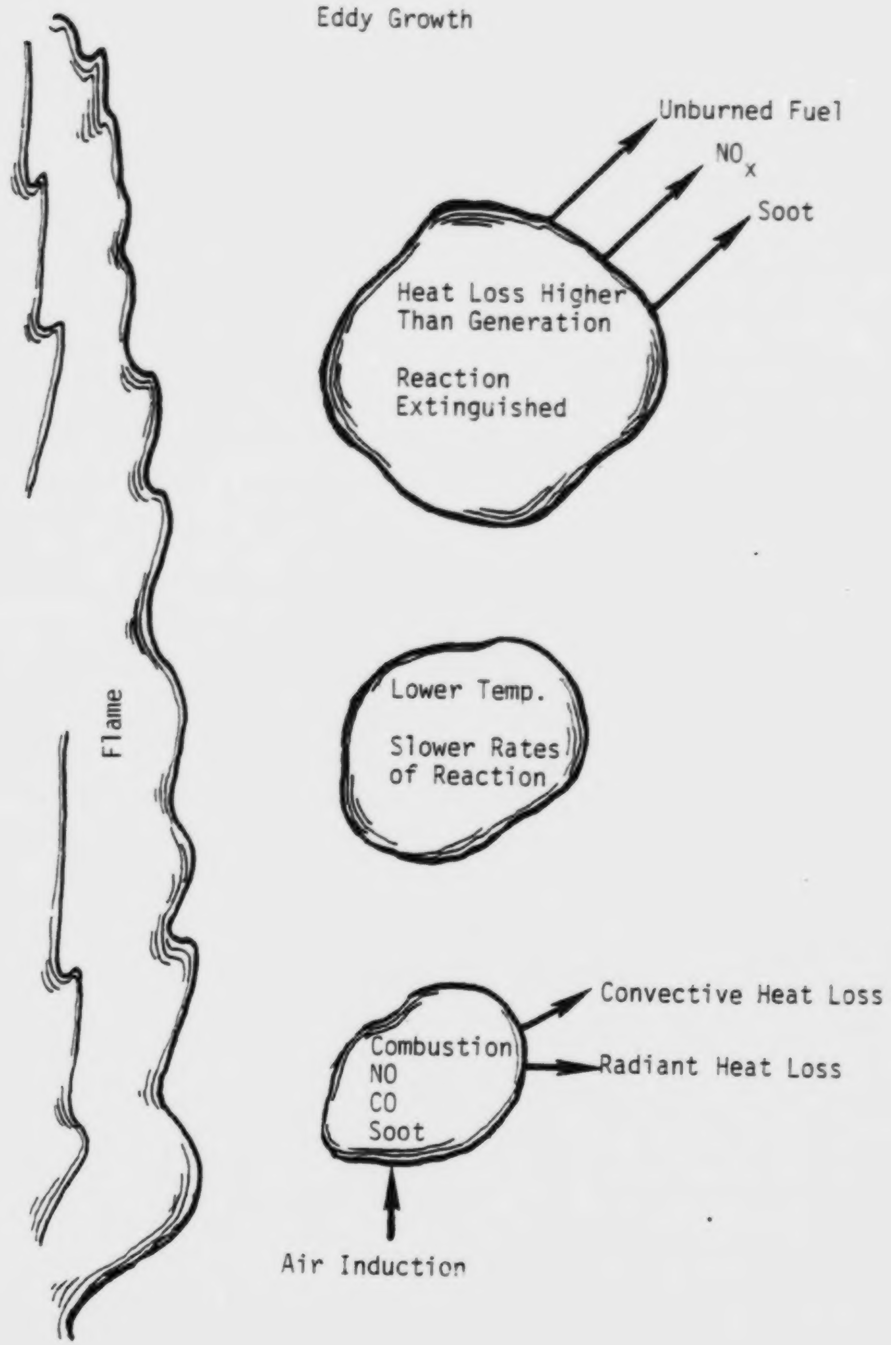
Eddy Growth
Unburned Fuel
NO_x
Soot
Heat Loss Higher Than Generation
Reaction Extinguished
Flame
Lower Temp.
Slower Rates of Reaction
Convective Heat Loss
Combustion
NO
CO
Soot
Radiant Heat Loss
Air Induction

Figure 2-24. Reaction and life of eddies shed from a flare.

must address the questions of formation, mixing, and reaction of eddies through their lifetimes.

Unfortunately, very little information exists in the literature concerning large eddies in turbulent systems and what does exist is inaccurate. Data from both Lee and Whipple (1981) and Howes, et al, (1981) indicate that an eddy will pass a sample point above the flare about every ten seconds. Photographic evidence by W. Brötz suggests that eddy size is on the order of a nozzle diameter. Gunther and Wittmer (1981) have taken measurements which may be interpreted as the size and the spacing between burning eddies. The size of eddies is on the order of the nozzle diameter, while the spacing between burning eddies is ten times greater. The development of large eddies in the shear layer and smaller eddies inside the jet was qualitatively shown by Wohl, et al, (1949) and measured by Ventura, et al, (1981).

Lee and Whipple (1981) observed eddies with concentrations of unburned hydrocarbons of about 10 ppm. Figures 2-25 and 2-26 demonstrate the quality of data obtained. These figures represent the results of probe sampling done above a pilot-scale two-inch flare by Lee and Whipple (1981). Lee's strip chart record of continuous CO data from the probe shows peaks corresponding to eddies passing the sample point. The peaks on the chart are smoothed out due to time lag in the sampling line and CO analyzer. Thus, while the frequency distribution of eddies in Figure 2-25 is probably accurate, the CO concentrations shown in Figure 2-26 are thought to be too low due to dispersion in sampling and analysis.

Brötz (1980) in his photographic study of pool flames measured eddy sizes for pool diameters of 3 to 12 inches and found eddy size had a weak dependence on pool size. As shown in Figures 2-27 and 2-28, eddies were generally elliptical with lengths ranging from 1 to 3 inches and widths from 1/2 to 2-1/2 inches. The large eddies contain most of the kinetic energy while the smaller eddies dissipated the kinetic energy to heat (Brötz, 1980). These figures show the size of the eddies observed and the nature of the problems associated with generalizing information about them.

Time Between Eddies Passing a Point Above the Flame
(Lee & Whipple, 1981)

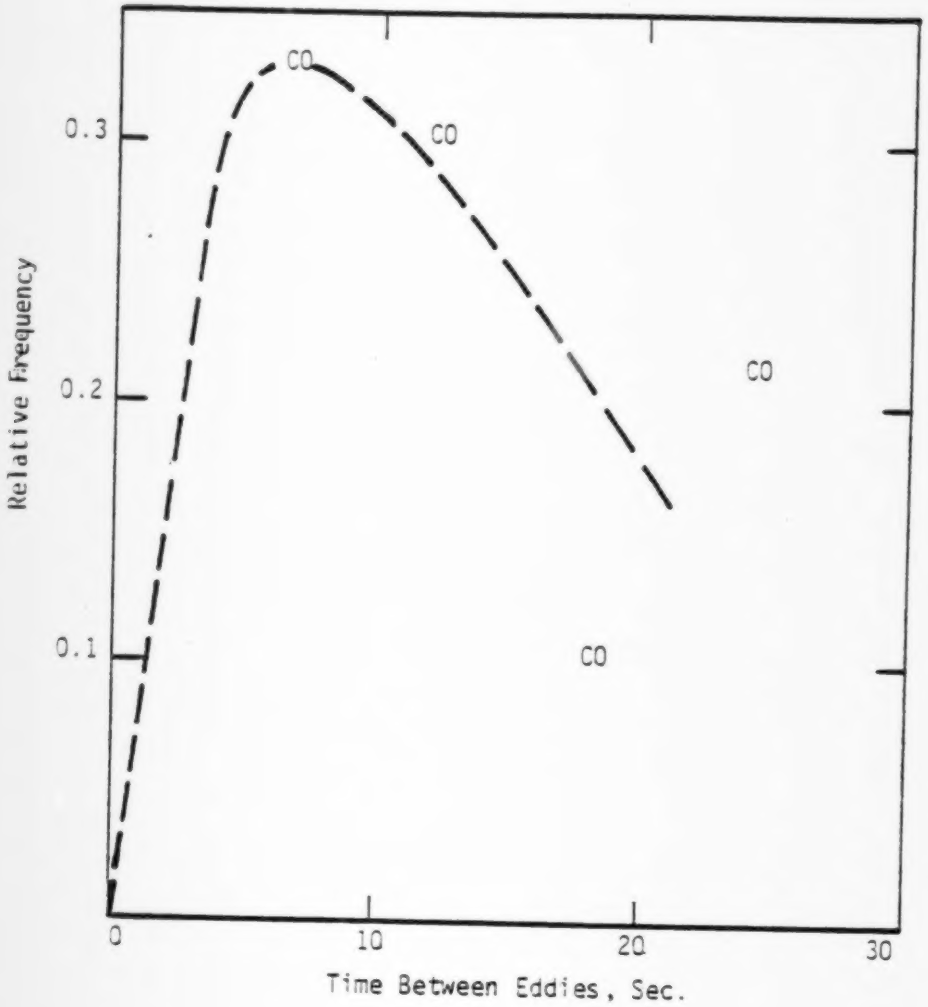

Figure 2-25. Eddy frequency.

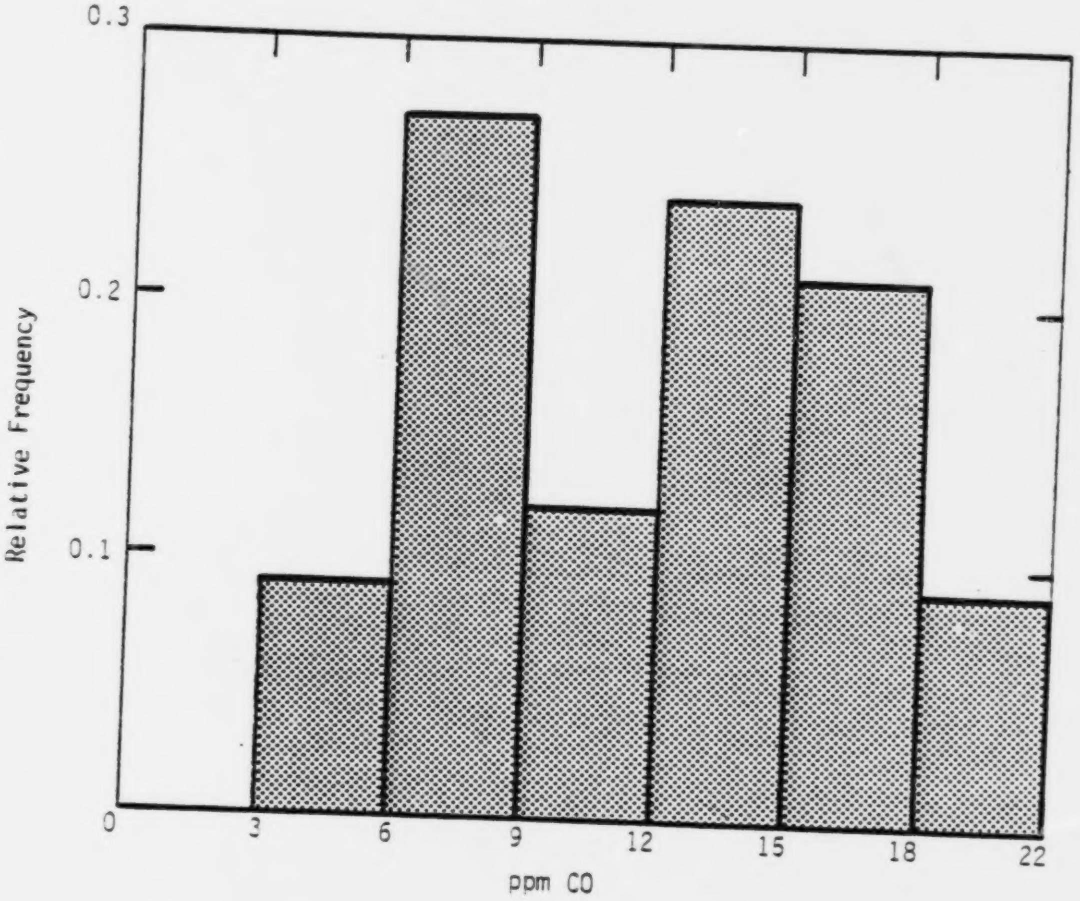
Relative Concentration in Completely Combusted Material in Eddies Passing a Point Above the Flame (Lee & Whipple, 1981)

Figure 2-26. Concentration of CO in eddies.

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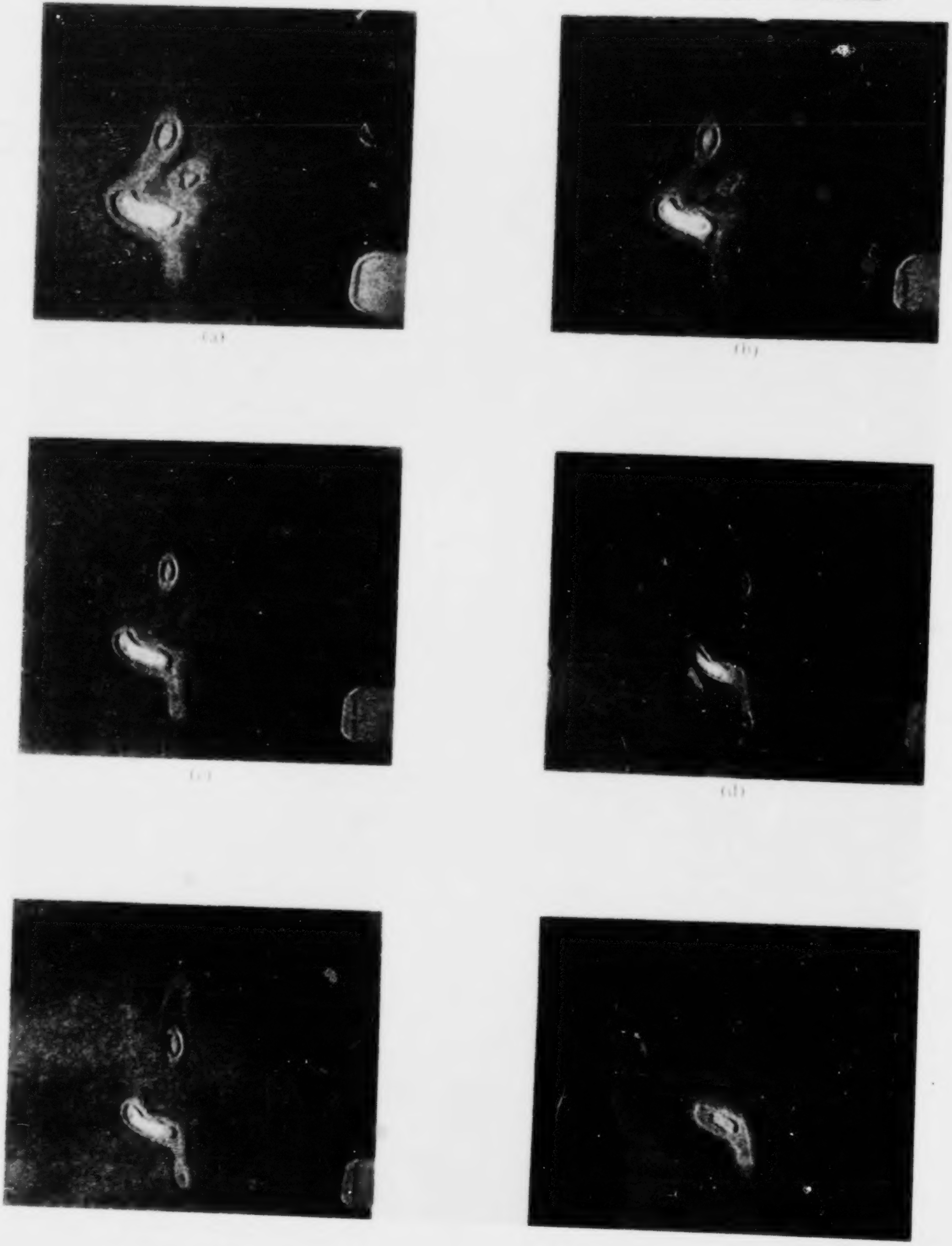

(a) (b) (c) (d)

Figure 2-27. Decay of an eddy from a pool fire. (Brötz, et al, 1980. Reprinted with permission of The Combustion Institute.)

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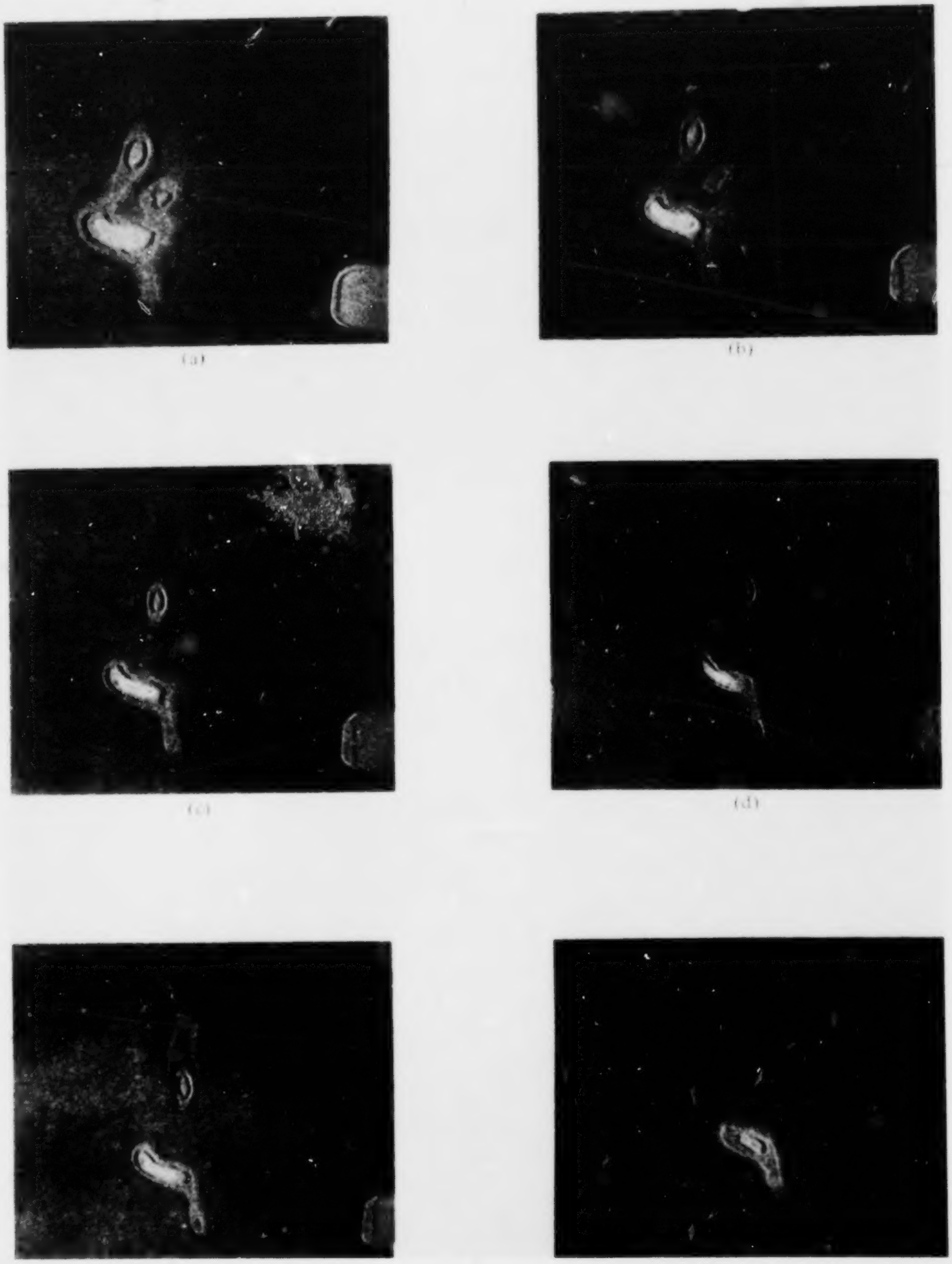


Figure 2-27. Decay of an eddy from a pool fire. (Brötz, et al, 1980. Reprinted with permission of The Combustion Institute.)

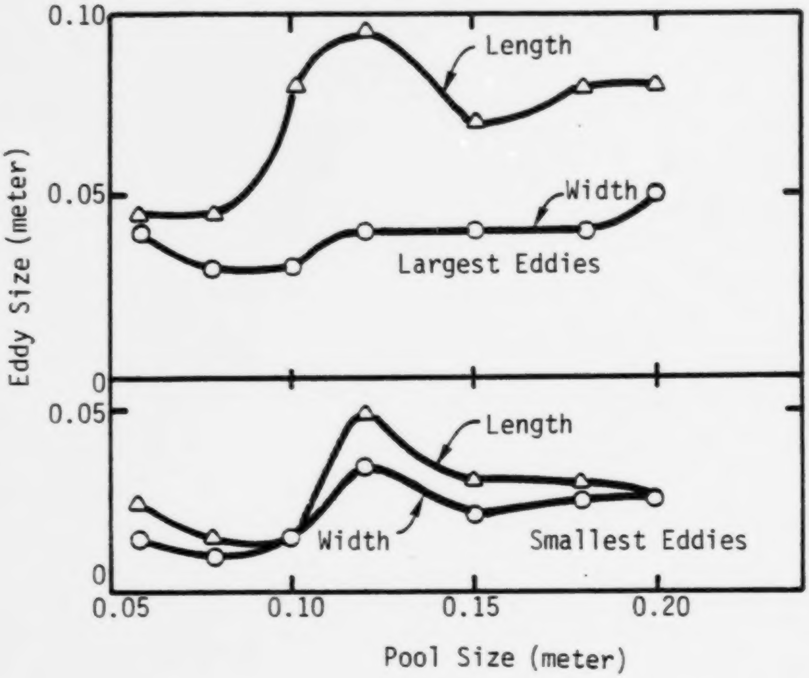


Figure 2-28. Geometric dimensions of the largest and smallest eddies in n-hexane pool flames as a function of pool diameter. (Brotz, et al, 1980; reprinted with permission of The Combustion Institute).

2.5.2 Previous Models of Jets

Past research on turbulent jets and flames leads primarily to an empirical understanding of certain gross observables pertaining to entrainment rates and flame lengths. Throughout the last 50 years, several descriptions of jet flames have been advanced with varied success. Most early work concerns flame length, which, although easily measured, is of secondary importance to a study of the efficiency of flares. The works of Abramovich (1969) and Hottel and Hawthorne (1949) are most notable in this area. In addition, some limited data exist on the effects of buoyancy and crosswinds on these principal observables.

In 1949 Hottel and Hawthorne noted that the single most important variable is the speed of the nozzle gas. At low velocities, a small laminar diffusion flame is present, the length of which steadily grows with increasing velocity until the laminar to turbulent transition region is reached. If nozzle velocity continues to rise, a slight brush appears at the flame tip and the turbulent flow spreads back toward the nozzle. Flame length reaches a maximum at the transition region and is shortened in the turbulent zone because of better mixing. Further increase in velocity has little effect save for shortening the small laminar potential core near the nozzle. This transition region normally corresponds to Reynolds numbers of between 2000 and 10,000 depending on the nozzle gas. The effects of velocity on flame type are shown schematically in Figure 2-29.

Ricou and Spalding (1961) developed models for the entrainment of air by turbulent fuel jets. Using a porous-walled cylindrical chamber and equalizing pressure with the atmosphere, the amount of air entrained by a jet was measured. Jets of fluid with densities different from ambient air were found to act differently, but data on non-burning propane, non-burning hydrogen, a premixed air-hydrogen flame, propane diffusion flames, and hydrogen diffusion flames were consistent with the equation for the forced convection limit:

$$\frac{\dot{m}}{\dot{m}_0} = 0.32 \frac{z}{d_0} \left(\frac{\rho_\infty}{\rho_0}\right)^{\frac{1}{2}}$$

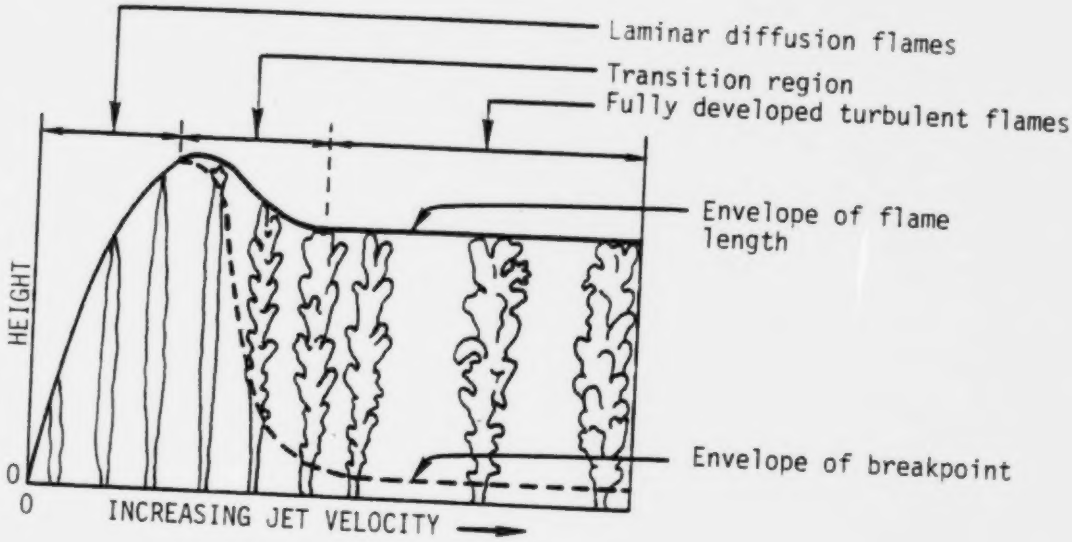

Laminar diffusion flames
Transition region
Fully developed turbulent flames
Envelope of flame length
HEIGHT
0
0
Envelope of breakpoint
INCREASING JET VELOCITY

Figure 2-29. Progressive change in flame type with increase in nozzle velocity (Hottel and Hawthorne, 1949; reprinted with the permission of The Combustion Institute).

where:

$\dot{m}$ = mass of entrained air

$\dot{m}_o$ = mass of jet fluid

z = axial distance from nozzle

d_o = nozzle diameter

ρ_∞, ρ_o = densities of ambient air and jet fluid, respectively.

Ricou and Spalding (1961) continued to demonstrate that theoretical scaling based on the Froude number, Fr, led to good predictions for the different flames. The Froude number is defined as:

$$Fr = \left[\frac{C_\infty T_\infty}{Y_f\ H + C_o(T_o - T_\infty)}\right] \frac{u_o^2}{g d_o} \left(\frac{\rho_\infty}{\rho_o}\right)^{1/2}$$

where:

C = specific heat of gas at constant pressure

T = temperature (absolute)

g = gravitational acceleration

Y_f = mass fraction of fuel in injected gas

H = heat of combustion of fuel

u_o = velocity at nozzle

Air entrainment by natural convection occurs faster than forced convection (but at different heights). Figure 2-30 shows the assymptotic limits of forced and natural convection. Figure 2-31 shows the correlation between theoretical and experimental values scaled by Froude number.

A study of a turbulent flame in a crossflow was done by Escudier (1972). Escudier proposed that fluid is entrained into the plume at a rate proportional to the velocity difference in both the horizontal and vertical directions. Thus, referring to Figure 2-32, the mass conservation equation may be written:

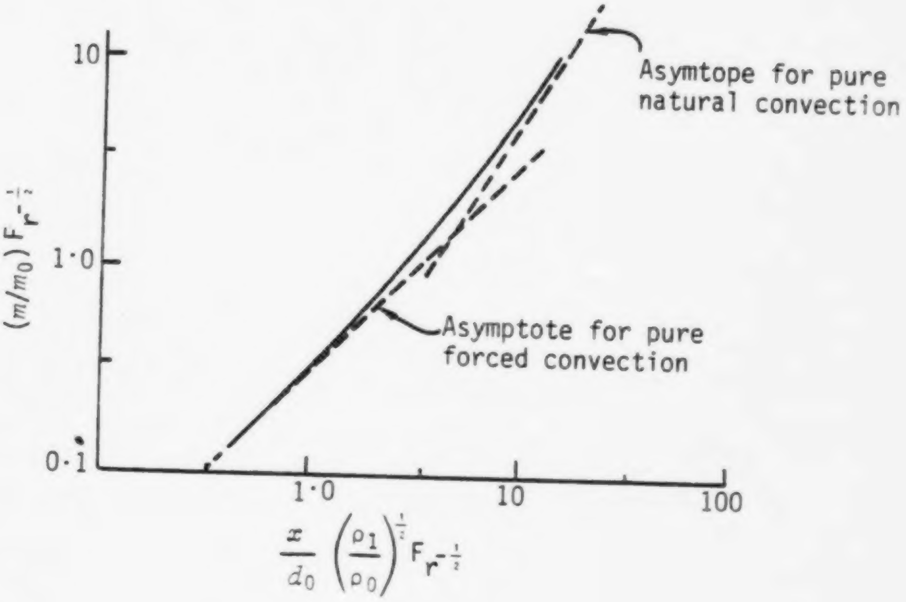


Figure 2-30. Theoretical prediction of entrainment in buoyant jets. (Ricou & Spalding, 1961; reprinted with permission of Cambridge University Press).

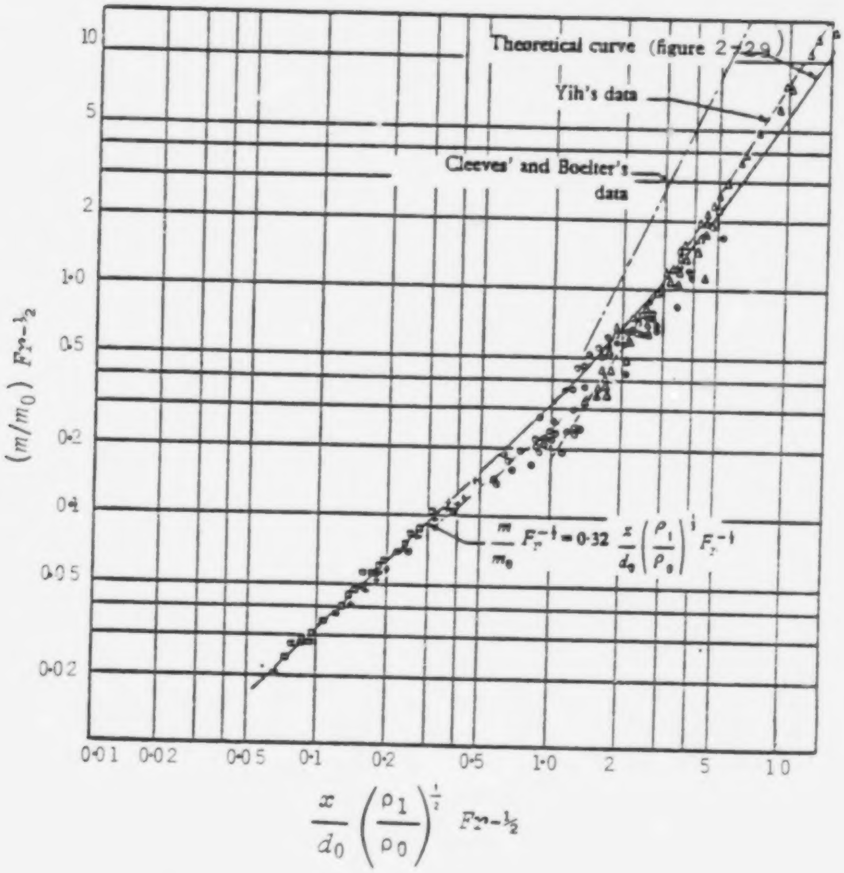


Figure 2-31. Entrainment by buyoant jets and flames. +, unburnt propane jet; □, unburnt hydrogen jet; ○, pre-mixed air-hydrogen flame; △, hydrogen diffusion flame; ●, propane diffusion flame (Ricou and Spalding, 1961; reprinted with permission of Cambridge University Press).

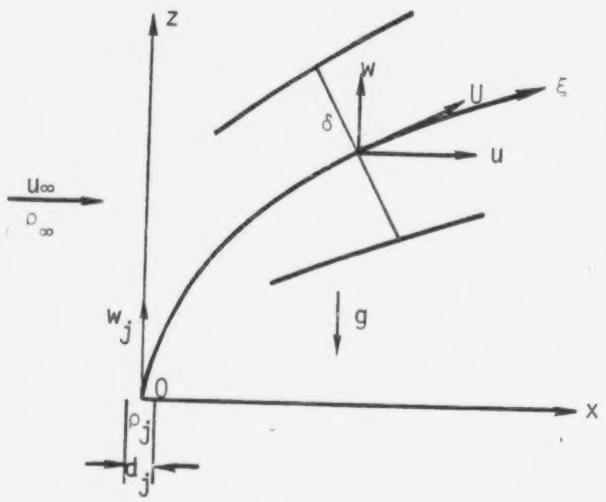


Figure 2-32. Definitions of x, z, the curvilinear coordinate ξ, horizontal and vertical velocity components u and w, velocity U, and flame radius δ. The gas jet discharges at velocity w_j with density ρ_j from a nozzle of diameter d_j into a cross stream of density ρ_∞ at velocity u_∞ .

$$\frac{d}{d\xi}\left(\rho\pi\delta^2 U\right) = 2\rho_\infty\pi\delta\left[\gamma\left(U - \frac{u_\infty u}{U}\right) + \alpha_E\left(\frac{u_\infty w}{U}\right)\right]$$

where γ, α_E are both empirical constants. Brzustowski, et al (1975) noticed that for Escudier's equation to reduce to Ricou and Spalding's without cross-wind and buoyancy, γ must have a specific value. Thus, we get

$$\frac{d\dot{m}}{d\xi} = 2\pi\rho_\infty\delta\left[0.08\left(\frac{\rho}{\rho_\infty}\right)^{\frac{1}{2}}\left(U - \frac{u_\infty u}{U}\right) + \alpha_E\,\frac{u_\infty w}{U}\right]$$

which assumes that we can extend application of the equation back to the nozzle ($\xi = 0$) with minor errors.

Brzustowski has also studied jets in a cross wind. He defines a burning rate parameter β by

$$\frac{d\dot{m}_p}{d\xi} = -0.233\,\beta\left(\frac{\Phi_p M_p}{\Phi_o M_o}\right)\frac{d\dot{m}}{d\xi}$$

where M_p, M_o are molecular weights of products and reactants, Φ_p, Φ_o are stoichiometric coefficients. Thus, β varies from 0 for a cold jet to 1 for a jet whose oxidation rate is limited by the entrainment rate. The general solution of these equations cannot be expressed in closed form. However, closed form solutions can be obtained for the case where $\alpha_E = 0$; i.e., buoyancy is negligibly small, and entrainment is given by the Ricou and Spalding equation. These solutions can be qualitatively compared with real flames to predict that high entrainment will cause a flare to bend over earlier. The limiting solutions are:

(a) $\dot{m}^* = \dot{m}/\dot{m}_o = 1 + 0.32\ \xi/d_o\ (\rho_\infty/\rho_o)^{\frac{1}{2}} = 1 + 0.32\ \bar{\xi}$

(b) $Y_p = \dfrac{-.0746(\Phi_p M_p/\Phi_o M_o)\beta\ \xi}{1 + 0.32\bar{\zeta}}$ = mass fraction of products

(c) $Y_f = \dfrac{1}{\dot{m}^*} - Y_p$

where

$$\bar{\xi} = \frac{\xi}{d_o} \left(\frac{\rho_\infty}{\rho_o} \right)^{\frac{1}{2}}$$

and

$$\text{(d)} \quad \bar{x} \equiv \frac{x}{d_o} \left(\frac{\rho_\infty}{\rho_o} \right)^{\frac{1}{2}} = \frac{1}{0.32} \frac{w}{u_\infty} \left(\left[1 + \left(0.32\, \bar{\xi} \frac{u_\infty}{w} \right)^2 \right]^{\frac{1}{2}} - 1 \right)$$

$$\text{(e)} \quad \bar{z} \equiv \frac{z}{d_o} \left(\frac{\rho_\infty}{\rho_o} \right)^{\frac{1}{2}} = \frac{1}{0.32} \frac{w}{u_\infty} \ell n \left(\left[1 + \left(0.32\, \bar{\xi} \frac{u_\infty}{w} \right)^2 \right]^{\frac{1}{2}} + 0.32\, \bar{\xi} \frac{u_\infty}{w} \right)$$

Near the nozzle, this may be approximated by

$$\bar{z} = 2.5 (w / u_\infty)^{\frac{1}{2}} \, \bar{x}^{\frac{1}{2}}$$

Define the flame length as the location beyond which mass flow of combustion products stays constant, then

$$\bar{\xi}_L = 13.4 \left(\frac{\Phi_o M_o}{\Phi_f M_f} \right) \frac{1}{\beta},$$

since at that point $Y_f = 0$. Note that at this location

$$\dot{m}^* (\bar{\xi}_L) = 1 + \frac{1}{0.233} \left(\frac{\Phi_o M_0}{\Phi_f M_f} \right) \frac{1}{\beta}$$

Under the above assumptions, this gives the dilution factor for a case when no fuel is burned. This model is then consistent when ξ, obtained from the flame length equation, leads to the observed dilution factor in the equation for entrainment. As an example, consider the combustion of propane which occurs via

$$C_3H_8 + 5O_2 \rightarrow 3\, CO_2 + 4H_2O$$

In this case, the following values are specified,

$$\Phi_f = -1,\ M_f = 44; \quad \Phi_o = -5,\ M_o = 32; \quad \Phi_p = 7,\ M_p = 29.1$$

where M_p is the average molecular weight of the products. For propane at ambient temperature and pressure, $(\rho_o/\rho_\infty)^{\frac{1}{2}}$ is 1.24 and leads to a flame length prediction of $60/\beta$ regardless of crossflow. The length of a turbulent propane diffusion flame has been found to be about 300 d_j, implying

β = 0.2 (Hottel and Hawthorne, 1949). This derivation is applicable only when the Froude number is large enough to neglect buoyancy effects.

In addition to presenting the limited case of a flame in the absence of buoyancy, Brzustowski presented a numerical solution to the 13 differential equations describing the general diffusion flame system. The parameter β was evaluated for the no-crosswind conditions by matching predicted and observed flame length and was found to be about 0.15. The empirical entrainment coefficient, α, was obtained with $u_\infty/w = 0.05$ at nozzle velocities of 15 m/sec and 57 m/sec. A value of $\alpha = 0.13$ matched the data quite well. Composition profiles are presented in Figure 2-33. Note that fuel and oxygen can exist together in this model since β does not have to be unity. The 13 equations solved are: continuity of fuel, intermediates, oxygen, products, and nitrogen; energy balance; horizontal and vertical momentum balance; total continuity; ideal gas equation of state; entrainment; definition of β; and a calculation of residence time. The method used for solving the system was not given.

Becker and Yamazaki (1978) presented their data for turbulent flames in a different form. They used the Richardson number which corresponded to the reciprocal of the Froude number. They also defined a near-field coordinate and a far-field coordinate.

Richardson number: $Ri = gd_o/u_o^2$

Near-field coordinate: $\xi = Ri^{1/3}\ z/d$

Far-field coordinate: $\xi\alpha = Ri^{1/2}$

They also defined a characteristic jet area with radius (b) such that at the radial position

$$\overline{\rho u^2} = 1/2\ \rho_c u_c^2$$

where $\bar{u}$ is the average vertical velocity at b and values with subscript c are center line values. The jet radius, b, may be expressed as a function of axial distance (z) from the nozzle with a spread coefficient, C_s.

$$b = C_s z$$

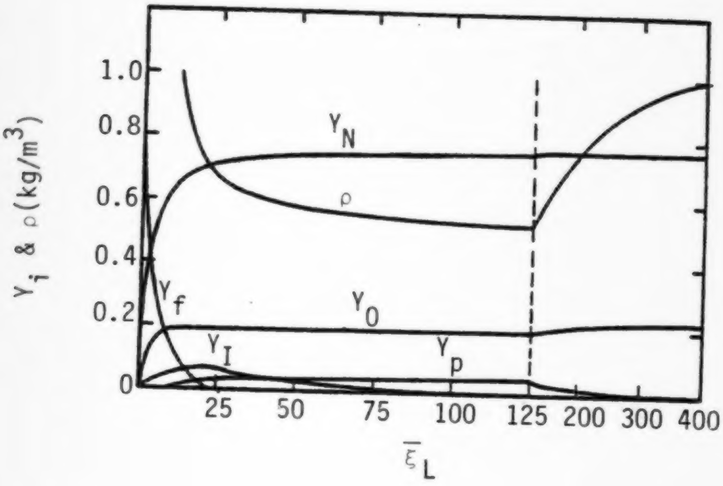


Figure 2-33. Computed profiles of composition and density for d = 0.005m, w = 22.1 m/sec, and u_∞ = 2.55 m/sec. (Note scale change at the end of the flame).

They found that up to ξ of about 5.5, C_s is constant at about 0.071. Beyond this, C_s increases, perhaps due to free convection buoyancy. Other derivations implied a C_s limit of 0.07 for forced convection and 0.10 for free convection. It is interesting to note that the flame jet appeared to emanate from a virtual origin about five diameters above the nozzle tips, while simple jet theory would predict a virtual origin of about three diameters below the nozzle tip. This may be due to boundary layer effects of the simple tube used in the study.

In contrast with Ricou and Spalding, Becker and Yamazaki define a different entrainment coefficient C_E such that

$$\frac{d\dot{m}}{dz} = C_E \, (\pi \rho \dot{G}/4)^{1/2}$$

where $\dot{m}$ and $\dot{G}$ are the jet momentum fluxes

ρ is the "mixing cup" density (stirred reactor).

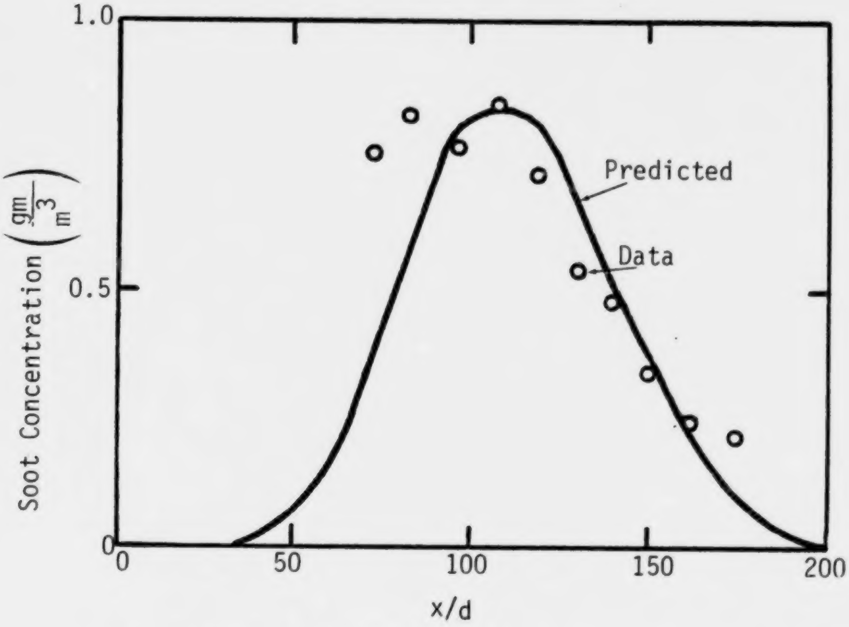
It was found that for ξ of 2 and ρ of 2.0, the entrainment coefficient, C_E, was 0.36. This value is different from the 0.16 found by Ricou and Spalding (Figure 2-31). Thus, the correct model is somewhat uncertain. Table 2-18 summarizes the data used by Becker and Yamazaki. Further discrepancies are evident when the free convection limit of 1.84 is compared with experimental results shown in Figure 2-31 which suggest a coefficient of about 0.60.

The studies discussed previously dealt with the aerodynamics and reactions of fuel jets. Magnussen (1980) developed a system of nine differential equations to describe soot formation. Some of his results are presented for an ethylene flame in Figure 2-34. Magnussen developed three kinetic rate expressions based on fuel, oxygen, and final products and used the one which would limit the reactions under the specific conditions. Without validation, a definite numerical solution would have only limited use and is probably beyond the scope of a study of flares.

In summary, results from the past modeling studies of burning jets are not consistent. The most recent work (Becker) contradicts the early results of Ricou and Spalding and does not suggest a method of reconciling the difference. However, the limited case solutions of Brzustowski (1975, 1976, 1977) may be used to predict the approximate nature of the flare.

TABLE 2-18. EXPERIMENTAL DATA USED IN THE STUDY OF BEKCER AND YAMAZAKI (1978) WITH PROPANE FUEL (REPRINTED WITH PERMISSION OF THE COMBUSTION INSTITUTE

Nozzle Meter d_o mm	Nozzle Gas Velocity u_o m/s	Mass Fraction of Source Material w	Nozzle Re_o	$10^5 Ri_o$	$\frac{\text{Length}}{\text{Nozzle Dia.}}$ L/d_o	Far-Field Steam Coordinate ξ_L	Flame End Re_L
5.63	3.5	0.0602	1310	443	128	21.0	5300
5.63	7.8	0.0602	2910	90.4	160	15.5	9400
5.67	17.5	0.0597	6570	18.1	195	11.0	17500
5.69	27.1	0.0594	10200	7.61	218	9.24	24300
5.71	42.0	0.0590	15800	3.19	246	7.80	35300
5.72	59.2	0.0588	22300	1.61	265	6.69	43700
3.25	76.9	0.0582	16400	0.55	278	4.91	30600
7.91	91.4	0.0602	48200	0.91	289	6.03	86000



x - axial distance

d - nozzle diameter

Figure 2-34. Experimental Soot Concentrations on the Axis of the C_2H_2 Diffusion Flame (Re=7000) Compared with Predictions (Magnussen, 1980).

2.5.3 Solutions of the Transport Equations

A general method of obtaining numerical solutions to the various partial differential equations (PDE's) governing the flare system would require prohibitive amounts of computer time. A mathematical model for predicting emission of pollutants due to incomplete combustion must include the following submodels:

- A two- or three-dimensional fluid dynamic code which accounts for the effects of backmixing, buoyancy, and density fluctuations of bulk flow.
- A turbulence model with coefficients that depend on local Reynolds number and which takes into account the mean density gradients and fluctuations. The turbulence model under consideration requires fully-developed turbulent flow with Reynolds numbers larger than 10,000. However, typical Reynolds numbers in continuous flare flames are less than 20,000 and the model will average all the dynamic responses of a flame.
- A finite reaction rate mechanism including a model of soot formation and burnout.
- An approximation which describes the effects of turbulence on mean reaction rates based on species and temperature fluctuations.
- A formulation of simultaneous gas and soot radiation.
- A model of radiation self-absorption which considers the intermittency of the turbulent flame.

For the most part, versions of each of the submodels are available, though integrating them for solution to the problems of flares using iterative PDE methods is difficult. Buildup of an overall flare model with the same level of sophistication as the submodels may yield a system beyond the handling capacity of present-day computers. The PDE methods available for solution to turbulent jet flames (Hutchinson, et al, 1976; Janicka, 1979; and Pope, 1981), usually neglect or simplify the chemistry and heat transfer. Solutions found by these complicated methods explain data no better than those obtained from much simpler approaches.

Solutions generated by PDE models are expensive and require a great deal of interpretation. For instance, just one PDE submodel developed by Dr. Wolfgang Richter of EER requires one-half an hour of run time on a CDC 7076 and costs several thousand dollars. Output from these models must then be converted to common engineering parameters for use in design.

In addition to being impractical, the existing models seem to be incapable of characterizing the fluid dynamics in flares and other practical systems, because previous mathematical modeling of turbulent free-shear layers (i.e., without a solid boundary) has been founded on basic notions which now appear to have little validity. These models do find useful application in cases where details of turbulent flow are not crucial. The calculation of flare emissions, however, requires detailed information.

Many attempts have been made to extend these early models to the prediction of complex turbulent phenomena. The results have been simply disguised curve-fitting with a multitude of model-parameters to be exploited to match theory with observation. The solution has been one of hiding our ignorance in ever more complex embellishments which include different averaging techniques (e.g., Favre, Chigier and Yule, 1979), multiequation transport models deduced from higher moments of the Reynolds time-averaged Navier-Stokes equations, the use of so-called scalar invariants, and the statistical manipulation of assumed probability-density-functions (pfd's) to obtain distributions of joint pdf's.

The basic flaw with this type of modeling of turbulent free-shear layers is the time-averaging of the equations of motion. The phase information associated with fluctuations is lost. This time averaging, in conjunction with so-called closure assemptions, has led to the notion of turbulent "diffusion" whereby matter is transported down velocity gradients in a dissipative manner and to the conclusion that mean quantities are distributed across a jet in a Gaussian fashion. Most notably, they fail to properly address the unmixedness aspect of turbulence.

The modern view of turbulent transport, based on experimental evidence obtained over the last few years, is at odds with the type of modeling discussed above. The new view, based in large part on the work of Roshko and his colleagues (1975) at Caltech, indicates that the basic transport mechanism is associated with long lifetime coherent elements of fluid (eddies) developed as a consequence of unstable inviscid motion. Although the transport is generated by the presence of a velocity gradient, it is not "diffusional" in nature and no dissipation takes place until final homogenization occurs and inviscid instability reduces the scale of inhomogeneity to the point where molecular diffusion dominates the process. Contrary to previous models, these eddies appear as coherent structures and retain their identity for long periods of time and may roll over ten times before they completely disintegrate to small scale structures. Hence, the phase, or coherence, information lost in time averaging is of first order importance in understanding turbulent entrainment and breakdown to the scale where molecular mixing dominates (the so-called Kolmogorov scale). This inviscid nature of eddy formation, coupling and instability is the subject of a number of current experimental and theoretical investigations.

Of particular interest in understanding turbulent chemistry and flames is the nature of the molecular mixing zones imbedded within the turbulent transport region. These are the strained interfaces between the fuel and oxidant inside an eddy as it breaks into smaller cells through instability. The culmination of this process yields a region of such fine scale (the Kolmogorov scale) that molecular diffusion is the dominant mixing process.

Models are being developed which are capable of accounting for the intermittent nature of turbulent flow and the presence of coherent structures which cannot be represented by time averaged statistics. Three such programs are being supported by the EPA through the Fundamental Combustion Research program managed by EER. Professor F. E. Marble has been developing a model that predicts the growth of interface surface area (ft^2/ft^3) within turbulent flames. The molecular diffusion process is then modeled as a simple self-similar strained laminar flamelet with a distribution of strain rates. EER has supplied the modeling of the finite-rate chemistry occurring in such flamelet zones. Professors J. E. Broadwell and P. E. Dimotakis (1980) are investigating turbulent macro- and micromixing both experimentally and theoretically. They have observed that in a turbulent jet the ratio of entrained fluid to jet fluid is remarkably constant throughout a cross section of the jet except in a rather narrow jet-edge region. (An explanation for the typically Gaussian distribution observed in earlier experiments is that the jet edge region continually passes back and forth across the observation point, thereby giving a statistical sample showing lower average concentrations as the measurement is placed farther from the nominal centerline.) Their work will make it possible to quantify the rate and stoichiometric distribution of molecular scale mixing in turbulent free-sheer layers.

Broadwell, on the basis of a re-examination of the early flame work of Hawthorne, Weddel and Hottel (1949) at MIT, and the above Caltech experiments has suggested a simple model of turbulent flame behavior. EER has undertaken flame chemistry calculations using this model for the purpose of developing an understanding of turbulent flame scaling. The work required to model flares is presented below.

2.5.4 Scaling Considerations

Scaling principles are the best available technique to interpret and extrapolate data from pilot scale flare flames. The following is a classical development of scaling principles for turbulent jet flames. However, an additional dimensionless group must be developed to account for the intermittent production of emissions and destruction of certain chemical species by turbulent jet flames. Dimensional analysis combined with some physical and chemical insight can provide some hints about the scaling of such flames. Dimensional analysis simply states that the number of parameters of significance in describing a phenomenon can be reduced by the number of fundamental dimensions required to describe these parameters. For our purposes there are four: mass, length, time and temperature. The resulting description relates variables and parameters which have all been made independent dimensionless groups. Clearly, scaling is fundamental to these notions. In the extreme, to deduce full-scale system behavior from experiments conducted at reduced-scale, all dimensionless parameters must be preserved and the dependence of system behavior on these parameters must be understood. However, this is seldom possible and the success of scaling depends on the ability to select and scale the most important independent parameter so that the dependent parameter of interest is reasonably modeled.

The dimensionless parameters can be deduced in a systematic fashion from the collection of first order dimensioned parameters, or they may be generated in a random fashion until the proper number of independent groups is obtained. The key to success in applying dimensional analysis is, of course, the insight to choose the proper set of first order variables. For a given flare gas composition, the concentration C_i of species i is a function of parameters as follows:

$$C_i = f(d_o, u_o, \rho_o, \rho_\infty, t_1, t_2, \ldots, t_n, \mu, c_p, T_\infty, T_{ad}, Q, L_{abs}, \rho_p, g, z)$$

where

d_o = initial jet diameter

u_o = intial jet velocity

ρ_o = fuel density

ρ_∞ = air density

t_1, t_2, t_n = characteristic times required for the various important reactions to go to equilibrium

ρ_p = combustion product density

μ = viscosity

c_p = specific heat

T_{ad} = adiabatic flame temperature - a measure of energy release

T_∞ = ambient temperature

Q = radiation intensity per unit volume of products

L_{abs} = absorption length for radiation

g = acceleration due to gravity

z = distance along the flame axis

The rationale for selecting some of the variables is obvious; however, there is no guarantee that all first-order variables have been included. The characteristic chemical times are, of course, temperature-dependent functions and their specification requires an assumption as to the proper set of chemical reactions. Viscosity is used here to represent all molecular transport coefficients of importance (or the ratio of these to viscosity). Viscosity is included in order to account for molecular mixing in thin "flamelets" in which temperature and stoichiometry may be of first-order importance. Adiabatic flame temperature is included to account for influences of temperature on transport and chemical behavior. The specific heat is included to account for change in temperature by energy loss. The radiation absorption length is temperature dependent and represents radiation of all species present. Finally, buoyancy effects depend on ρ and g. Forming dimensionless groups we have:

$$C_i = f\left(\frac{t_o}{t_c}\,,\ \mathrm{Re},\ \mathrm{Ri},\ \rho_o/\rho_a,\ \frac{t_o}{c_p T_{ad}/Q}\,,\ \frac{L_{abs}}{d}\,,\ \frac{z}{d}\right)$$

where

t_o = d_o/u_o

t_c = is used here to be representative of all the chemistry time constants

Re = $\rho_o u_o d_o/\mu$ (Reynolds number)

Ri = $\frac{(\rho_a - \rho_f)}{\rho_a}\, dg/u_o^2$ (Richardson number)

For simplicity, the many ratios of molecular transport coefficients (such as Prandtl number), chemical time constants, and molecular properties of individual species have been omitted.

By dimensional arguments, t_o is proportional to overall flame residence time at a given z/d. The quantity $t_o Q/c_p T_{ad}$ is a measure of the normalized temperature decay due to radiation without self-sbsorption, L_{abs}/d is relative measure of how much the flame self-adsorbs the radiation. L_{abs} is typically one meter, hence flames with characteristic widths of a meter or more behave very differently than bench-scale flames with narrow flame widths. Richardson number is a measure of buoyancy effects and the Reynolds number compares inertial to viscous forces.

Exact scaling would require the preservation of all demensionless groups, but an examination of the groups shows that a reduction in scale would be impossible. If, however, the effects of Re and Ri number are relatively small, a preservation of the characteristic time, t_o, will maintain similarity at different scales except for the change in self-absorption of radiation.

The reduced-scale flame will operate colder due to reduced self-absorption because the parameter L_{abs}/d is smaller. Mathematical modeling can help determine the effect of neglecting the scaling of some dimensionless groups. Thus, experiments may be designed to produce data useful for scaling without scaling all dimensionless groups together. As an example, in reducing the scale it may be advantageous to operate at reduced t_o in order to elevate flame temperature by lowering radiation intensity to partially compensate for reduced absorption. This is the type of trade-off, deduced from mathematical modeling, that allows the design of an optimum reduced-scale system.

Once the independent variables have been established, experiments may be designed to change one variable at a time and to correlate the results with the model of flare behavior. An example of this technique is to let C_i represent unburned hydrocarbons. In this case, t_c would be the characteristic time needed to burn the hydrocarbons. The Reynolds number may be unimportant in a low momentum flare, but the Richardson number should be quite important. The density ratio and radiant heat loss should both be important. Self-absorption of radiation may be quite small in a small flare; however, if the eddies in real flares are small, then the heat lost in eddies by radiation may also be unimportant. Thus, in the case of a low momentum flare, we might fix nozzle diameter, chemical reaction time (temperature), density, and radiant emissions while correlating combustion efficiency with dimensionless time and Richardson number.

Experimental studies carried out with the sole objective of investigating scaling phenomena have been few, and consequently there is little experimental support for models which relate to the definition of scaling criteria. Often the approach taken experimentally has been one of partial modeling, where interest is restricted to the attainment of similitude only of certain aspects of the combustion process (e.g., heat transfer, pollutant emission) at different scales. From a practical point of view, scaling criteria (whether fundamental or empirical) are required to provide information with regard to the design of subscale experiments, and particularly to the specification of equipment (e.g., size and throughput), such that the performance of the full scale counterpart can be reproduced or predicted. Studies carried out to date show, however, that exact similarity of a combustion process in all respects, at different scales, is almost impossible to achieve. This further confirms the need for an improved understanding of the more fundamental controlling mechanisms, supported by mathematical modeling, in order to produce scale related information.

For future studies, the application of the usual flare system design procedures to the specification of a subscale experiment, would result in a flare head design where gas exit velocities are the same independent of scale. (The design basis is usually one which calls for an exit velocity equal to 0.2 Mach number.) This constant velocity scaling approach is often adopted in the design of burners for enclosed combustion systems, where manufacturers are interested primarily in maintaining constant windbox pressure. Experimental studies (Salvi and Payne, 1980) have shown, however, that constant velocity scaling does not result in good overall similitude, particularly near the limits of stability. This is attributed to a reduced residence time, as defined by the ratio of a system characteristic dimension divided by velocity, in the important (high temperature) regions of a flame at the reduced scale.

An alternate scaling approach, one suggested by the dimensional considerations above in the absence of buoyancy and heat transfer effects, is that of constant (mean) residence time. In this approach, velocities are reduced in the small scale experiment to maintain constant residence time for a given (scaled throughput). Care must, however, be taken here to avoid a situation where, at very small scales, the velocities are so low that the turbulent characteristics of the flow lie in a different regime. The constant residence time scaling approach has also been investigated by Salvi and Payne (1980) and has shown that good similarity in terms of overall flame characteristics can be achieved. However, it was consistently observed in these studies that the chemical flame length was shorter in the smaller scale than in the larger one at corresponding conditions. This is illustrated by the data of Figure 2-35 where the macromixing (as characterized by the mixing factor) is well simulated at different scales, while the micromixing (as characterized by burnout degree for these gas flames) shows burnout is more rapid for the smaller flames. These observations confirm the importance of turbulence and turbulent mixing parameters which may differ with the scale of the flame.

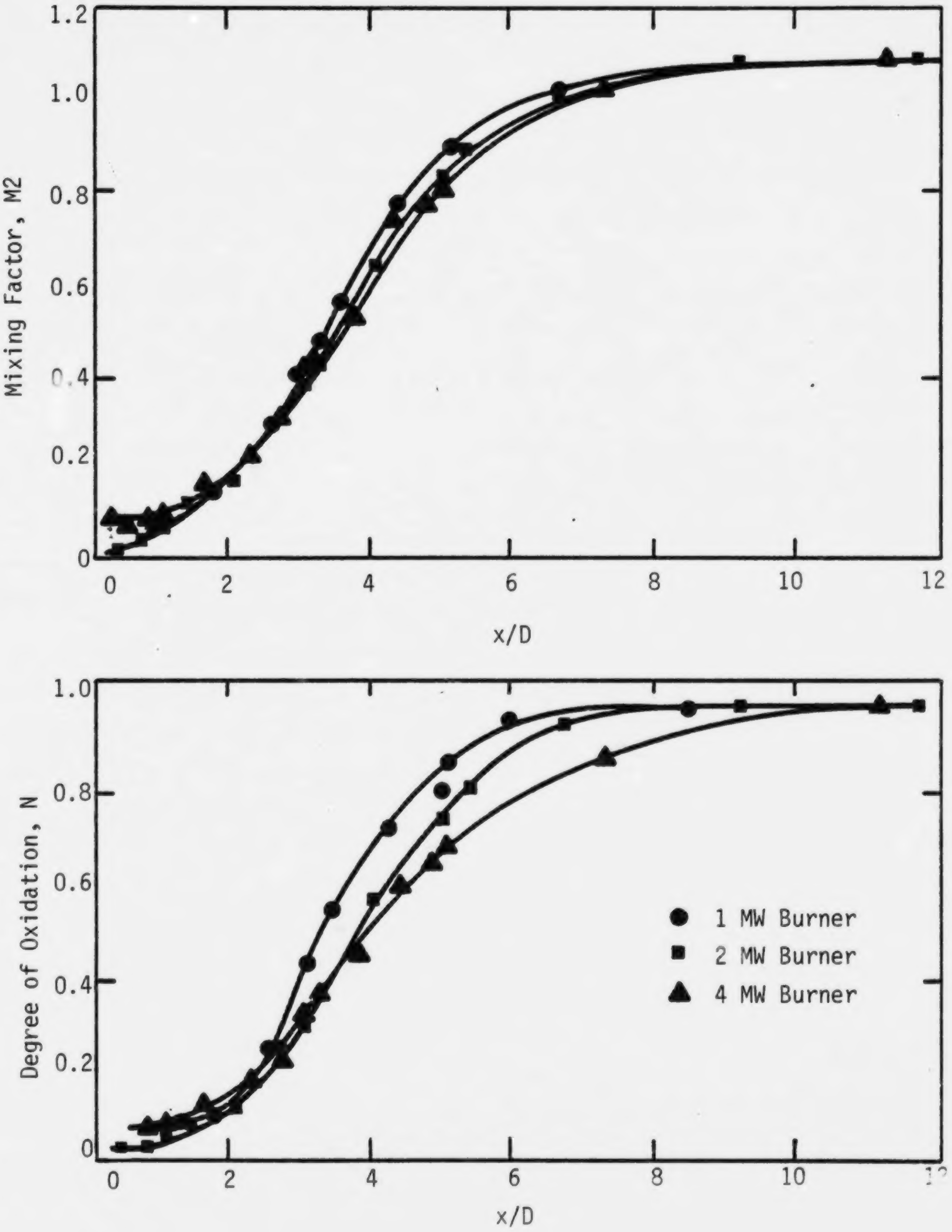


Figure 2-35. Mixing factor (M2) and degree of oxidation (N) for "Constant Residence Time" scaled natural gas flames --axial traverses (Salvi and Payne, 1980).

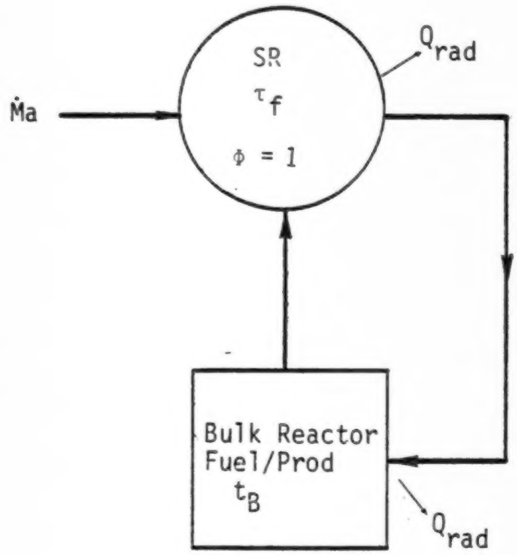
2.5.5 The Broadwell Model of Turbulent Flames

Mathematical models of flares should be applied where feasible in the flare program. However, the use of dimensional analysis cannot be rigidly applied because it requires experimental verification. Considering the uncertainties in our knowledge of turbulent flame behavior and our need for scaling and extrapolation, it is desirable to use the simplest model which can predict the essential features of turbulent flames. J. E. Broadwell has suggested such a model during his EER/EPA-sponsored investigation into turbulent behavior. It incorporates several basic notions:

- The macroscopic entrainment rate is uniform across the jet. This is based on experimental studies at Caltech (Broadwell and Dimotakis, 1980) showing entrainment to be approximately constant except at the jet edge. The rate of entrainment in the model is consistent with the observations of Abramovich, Spalding and others.
- The microscopic mixing rate at the molecular level is a fixed fraction of the macroscopic entrainment rate. Flame length data, interpreted in terms of micromixing, confirm this over a wide range of fuels and conditions and indicate that the fraction is approximately one-third.
- During the process of eddies cascading to smaller and smaller scales, the eddies of fuel and entrained fluid break down and the interfacial surface area grows slowly until the end of the process where the Kolmogorov scale is approached. Thus, the model assumes that the dominant molecular diffusion flame behavior occurs at the Kolmogorov scale (λ).
- Since reactions are fast, the Kolmogorov scale flamelets are assumed to consume the entrained air at the stoichiometric ratio with a subsequent mixing of the products with the fuel.
- For simplicity, the strained flamelets are modeled by a well-stirred reactor with a time constant equal to that required for complete mixing at the Kolmogorov scale, i.e., $t\alpha\lambda^2/\mu$ = kinematic viscosity.

- The resulting bulk fuel/product stream which feeds the flamelets is modeled as a simple plug flow reactor.

This model has been programmed at EER utilizing EER's basic chemical-kinetics reactor subroutines coupled in such a manner as to allow the feedback indicated above. Radiation heat loss is allowed for from both the flamelets and the bulk flow by allowing for self-absorption based on the characteristic dimensions of the flame. Schematically, the model appears as sketched below:



where

Q_{rad} = radiation heat loss

SR = stirred reactor

τ_f = flamelet residence time

ϕ = stoichiometric ratio

t_B = "cooking" time in the bulk reactor corresponding to its position along the flame

$\dot{m}_a$ = microscale air entrainment rate

EER has used the model to predict the NO generation in the hydrogen-air turbulent flames of Bilger and Beck (1975) with the results shown in Figure 2-36. The NO versus axial position data were obtained at several values of Re and t_0 with fixed Ri. The model incorporates two parameters which can be varied to fit experimental data, thus making results flexible and practically useful. One pertains to the degree of radiation self-absorpion and the other to the proportionality constants appearing in the formulation of the Kolmogorov time constant. Both of these were varied within a reasonable range of uncertainty in order to match the Bilger and Beck data at one x/d and one operating condition. Then, the remainder of the predictions were made without further adjustments. The results are encouraging and lend credence to the notion that turbulent flames can be scaled with a relatively simple model.

As further information becomes available on the detailed behavior of chemical reactions in turbulent jets, the model used should undergo revisions. Such information is currently being generated at Caltech under an EER/EPA sponsored program. A number of potential improvements which could be made using the information from the EPA/FCR program are:

- Improve the macromixing model as required to reflect a distribution of entrainment rates across the jet, especially at the edge where quenching may be important.
- Incorporate a distribution of entrainment eddy sizes which will result in a distribution of breakdown times and hence micromixing rates.
- Incorporation of an inviscid fluid mechanics code to predict the unstable break up of eddies.
- Allow for the microscale strained flamelet occurring at the interfacial surface prior to complete breakdown if experimental evidence warrants it.
- Model the flamelet behavior as a strained diffusion flame with a distribution of strain rates rather than a simple stirred reactor.
- Use a multizone radiant heat transfer model to more accurately predict heat loss from the flame.

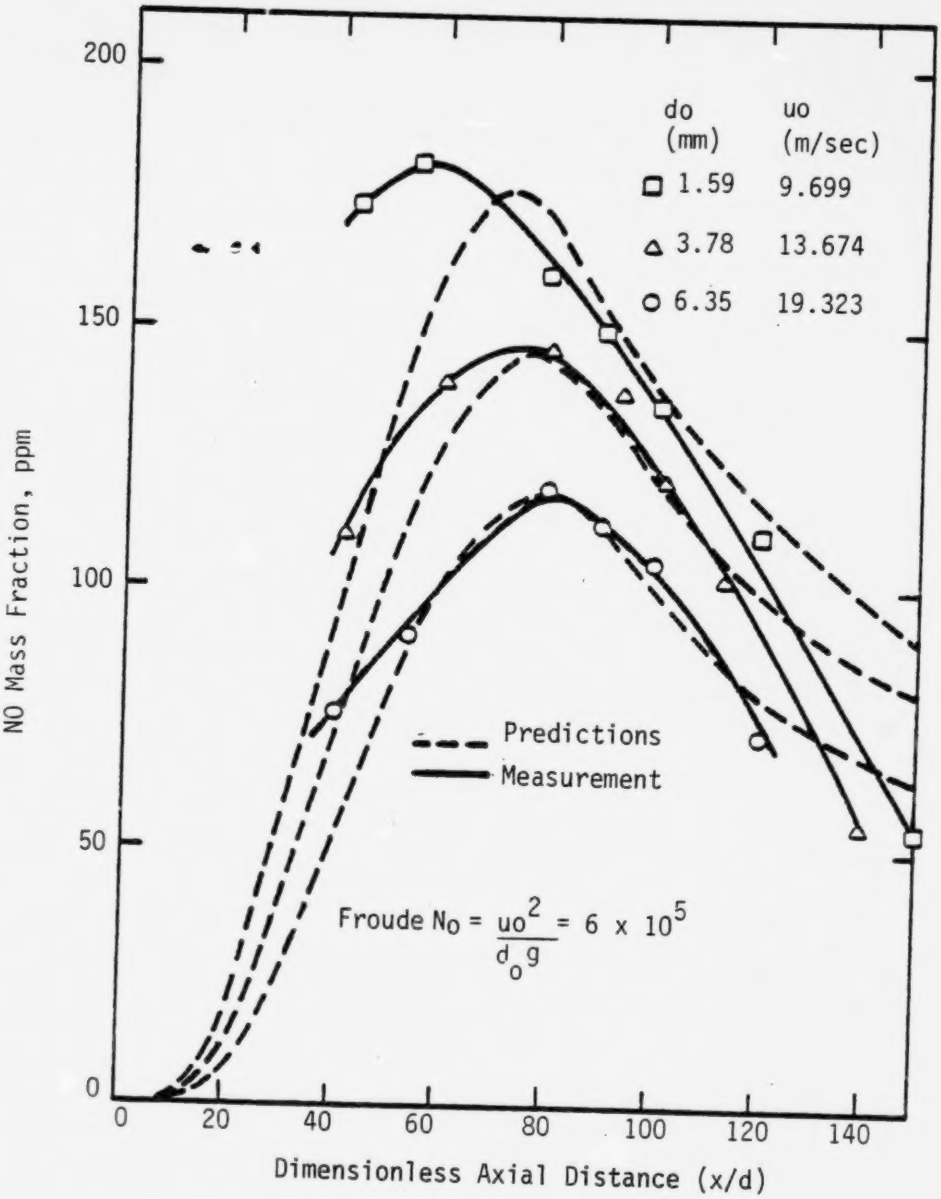


Figure 2-36. Comparison of model predictions of NO mass fraction against measurements of Bilger and Beck (1975) for hydrogen-air flames for x/d >30. The prediction indicates a frozen NO flux, whereas the data indicate NO destruction. (Reprinted with permission of The Combustion Institute.)

2.5.6 Recommendations for Modeling of Flares

Flare scaling is complicated by buoyancy, crosswind, radiation heat transfer, and Reynolds number effects which preclude pure residence time scaling. However, relatively straightforward modeling techniques may be used as a guide for design and scaling. The dimensional analysis approach mentioned previously should be supplemented and guided by mathematical models of the type being developed by Broadwell.

It is recommended that a model similar to the Broadwell turbulence model be modified to improve the heat transfer components and to include measured and/or empirical correlations for the frequency of production of eddies of different size, entrainment rates caused by crosswind, and buoyancy effect. The model should incorporate the ability to screen chemical reaction rates so that reactions leading to or inhibiting chemical destruction can be isolated.

Scaling and models could then be used to help design near optimum subscale flares with characteristics similar to industrial flares so that the results can be extrapolated with confidence. After taking measurements on subscale flares, the models should be "fine-tuned" to represent the data before extrapolation to full scale.

3.0 THE NEED FOR WORK

Previous sections have reviewed some of the existing information which is potentially useful in establishing a future program to evaluate flare efficiency. This information demonstrated that:

- Flares are widely used, the most economic means for disposing of waste gases, and for the foreseeable future elevated flares will remain the only reliable means for safely disposing of large quantities of gases and vapors in emergencies.
- Emissions of incompletely burned fuel from flares can contribute to the emissions of hydrocarbons, carbon monoxide, and soot from stationary sources.
- Information available on flares is insufficient to estimate emissions from flares or to relate results from one flare to another.

In spite of the widespread use and potential emissions of flare systems, relatively little quantitative information is available, particularly concerning the use and performance of elevated flares. This is true with regard to all aspects of flare operations, from a lack of knowledge of the quantities and compositions of gases flared to a lack of actual performance data on individual flare systems.

There is, therefore, an urgent need for research to determine efficiencies of and emissions from flare systems. Research objectives include development of appropriate measurement methods and techniques which can be used to establish and validate modeling approaches, establishment of emission factors, and development of a data base relating emissions to flare design variables. Such information is needed to design experimental flares capable of establishing the emissions from commercial flares, in order to understand how design and operation of flares affect emissions.

Few estimates of the amount of gas flared in the United States have been made and the ones that have are probably highly inaccurate. Part of the uncertainty results from the large amounts of gases that are released during emergencies at uncontrolled and unknown flow rates. However, some estimates of the gas flared have been made. The estimate of the amount of gas flared by Klett and Galeski is compared in Table 3-1 with those of this study. The values

TABLE 3-1. ESTIMATE OF GASES FLARED IN THE UNITED STATES

	Klett & Galeski (1976)	This Study (1980)
Refineries	1.3	2.1
Coke Ovens	0.4	0.2
Blast Furnaces	9.8	9.6
Ethylene	0.2	---
Chemical	0	1.2
Oil Production	0	2.9
Total	11.7	16.0

are comparable. The major difference is the increase in petroleum refining, and inclusion of the entire chemical industry and petroleum production. Nonetheless, both estimates are suspect because much of the data do not exist and the data available are incomplete, contain large variations, and possibly contain large errors.

Information is lacking from full scale flare system because of the problems associated with making measurements in large, elevated uncontrolled flames. These are obvious and include problems due to intense heat radiation, flame mobility, susceptibility to external forces such as wind, and inaccessibility to suitable sampling locations. Measurements are therefore extremely difficult, expensive to make, subject to errors, and difficult to interpret. For these reasons much of the work carried out concerning flare systems has been at small and pilot scale where some degree of control over the experiment can be exercised, and where measurements can be made with more accuracy and less expense.

The contribution made by previous experimental work on small scale flares has been reviewed in Section 2. In spite of several detailed studies, it has been impossible to conclusively identify the amounts of incompletely burned fuel emitted from a flare. The review of this work suggests that measurement difficulties continue to be a major problem and that deficiencies lie in four main areas:

1. Material balances could not be closed. Therefore, the accuracy of the measurements could not be confirmed and incompletely burned fuel could escape the flare undetected.
2. Soot was not systematically measured. Consequently, the emissions of incompletely burned fuel could have been underestimated by the amount of soot emitted.
3. The experimental techniques used could not adequately account for incompletely burned fuel escaping in highly intermittent eddies. Again, this error tends to underestimate the emissions from flares.
4. Scaling principles were not developed or available to allow the experimental results to be extrapolated to commercial flares of different sizes, geometries, and operating conditions. Without such a methodology, estimates of emissions from individual flares and total emissions from the population of flares could not be made.

Incomplete Material Balances

In only one previous study (Siegel, 1980) was an attempt made to close a global material balance. Only about 50 percent of the emitted gas could be accounted for as measured combustion products. Siegel attributes this to the difficulty of measuring off-gas product velocity, which fluctuates rapidly in magnitude and direction above the flare flame. He thus concentrated on "local" burnout values which needed no velocity measurement. A material balance check must substantially close if confidence is to be placed in global efficiency values.

Emissions were estimated in previous studies by measuring time-averaged concentration of incompletely burned species in a plane above a flare, and attempting to calculate total emissions by integrating these values. There are potential errors with this approach, and the nature of the errors depends on the technique used. One or more of the following errors were made in all previous studies:

- Material affecting emissions passed outside the plane of measurement, or was below the detection limit of the analytical equipment.
- Concentrations of some incompletely burned species were not measured. The concentration of soot has not been adequately measured in any study, and in some studies CO has been inadequately measured.
- Techniques used to integrate local and instantaneous combustion efficiencies have been inadequate. A number of assumptions and simplifications have been made in order to facilitate integration, but none of these have been justified and some of the simplications may result in significant errors in calculating overall efficiency.

In any future experimental work, it is therefore essential that the question of closing the material balance be properly addressed and given the highest priority if reliable efficiency data are to be obtained.

Measuring Soot Concentration

In the previous studies, only Siegel and Howes, et al have measured soot concentration. However, very few measurements of soot concentration were made in these studies and those that were could not be used to determine the effect of soot on overall efficiency. Siegel measured soot concentration in four tests and found values between 20 and 80 mg/m^3. He estimated that accounting for the soot would decrease flare efficiency between 3 and 4 percentage points, a large number compared to his estimates to efficiency for non-sooting flares. Howes, et al measured soot concentration of 0.1 - 20 mg/m^3 in five tests. The efficiency loss caused by production of soot was not included in Howes, et al calculation of local efficiencies.

The soot measurements of Siegel and Howes, et al indicate that production of soot can contribute to the inefficiency of flares. Calculations shows that for propane fuel and an expected dilution of 1000, 15 mg/m^3 of soot corresponds to a one percent loss in efficiency. Consequently to accurately determine the efficiency of flares, soot concentration below 15 mg/m^3 must be accurately measured.

Therefore, during test conditions producing any visual evidence of soot formation, soot must be measured simultaneously with gas concentration at all locations. The loss of efficiency due to soot concentration can then be added to the local loss of efficiency due to other incompletely burned species and integrated over a flux plane large enough to include all the species of interest and yield the overall efficiency of combustion.

Errors Caused by the Intermittent Nature of Flares

The mildly turbulent, highly intermittent nature of the flare flame makes accurate measurement of the emission of incompletely burned species difficult. Available information would seem to indicate that most of the incompletely burned species appear to be the result of quenched eddies at the edge of, or within a flare flame. Consequently, the incompletely burned material emitted in this way must be carefully identified and measured if efficiency is to be accurately determined.

Scaling Principles

Previous studies were conducted in pilot-scale flares (Palmer, Lee and Whipple) or industrial flares (Siegel and Howes, et al). No method was provided in these studies for extrapolating the emission data to flares of different size and geometry or to the population of commercial flares. Experiments on the emissions of incompletely burned fuels from flares must be modelled or scaled so that results can be properly interpreted, properly understood, and extrapolated to other flares.

Scaling of flares is difficult, because it is not possible to scale all the dimensionless numbers simultaneously and maintain a flame. Recently, work by Salvi and Payne (1980) has begun to isolate the important scaling parameters for large flames. The available information on scaling has been summarized and supplemented in Section 2.5.

From the above considerations, it is apparent that further experimental work is required in order to quantify emissions from and efficiency of flare flames. In view of the difficulties inherent in the measurement of large elevated flames, any future work must of necessity be carried out at small or pilot scale where at least some of the problems are more manageable. This could ultimately include tests on small commercial flares at ground level. This work must define and prove an experimental method which removes some of the deficiencies identified in previous studies. Key to this method must be the use of measurement techniques which permit the identification of the source and mechanism of inefficiency, if any, in a flare flame, and then the closure of a mass balance to account for all of the input fuel. In addition, aspects of the problem which relate to scaling must be addressed if results are to be interpreted and translated to the population of industrial flares.

From the review of literature, it would appear that one of the most significant factors which has precluded a quantitative knowledge of flare efficiencies has been a lack of basic understanding of the processes which occur in even the simplest of turbulent diffusion flames. Much of our lack of understanding is related to the effects of mixing on the combustion process and to the presence and effects of coherent structures within a flame. There is evidence to show that in flare flames, the majority of the combustion process occurs at the surface of many detached eddy flames, and it is believed that an understanding of the role played by such phenomena is key to establishing flare efficiency. In experimental work, measurement techniques are, therefore, required which take into account the intermittent nature of the flow and provide a means for integrating results both in time and space. A number of more fundamental studies are currently in progress which are investigating, and attempting to model, combustion systems by describing the mechanisms of eddy formation and decay. Linking these efforts to a flare study offers the potential for providing the kind of information which can both guide experimental work and provide a means for the interpretation of experimental data.

The scaling of experimental results continues, however, to present problems, mainly due to a lack of experimental data directly related to scale, and a dearth of large scale data on which to base extrapolations. Further information on scaling methods is therefore required before information gathered at small and pilot scale can be confidently transferred to the variety of commercial systems found in practice. Because of the present lack of experimental data, a sound modeling base is required which is capable of calculating combustion efficiency and partial oxidation products and which can provide a tool for the interpretation of data obtained at different scales. While a number of combustion models incorporating varying degrees of complexity are in existence, none would appear to be directly applicable to the problem of elevated flares. A new or slightly modified approach is therefore required which avoids unnecessary complexity and uses both empirical and fundamental information to describe the phenomena which control flare combustion. The elements for such a model are available, but validation against reliable experimental data is required for selected representative cases.

In the following sections, an experimental program is proposed which is aimed at providing data for determining flare efficiency. Primary consideration is given to the choice of an experimental approach which attempts to avoid some of the deficiencies of earlier experiments and which provides data which can be used to determine scale effects.

4.0 TECHNICAL APPROACH AND EXPERIMENTAL PLAN

In previous sections, the need to determine emissions of hydrocarbons from flares has been discussed, and areas where further work is required have been identified. Previous experimental studies aimed at addressing this problem have been shown to have a number of deficiencies which must be overcome if any further work is to be meaningful. The conclusions drawn from the preceeding discussion suggest that a program established to determine flare efficiencies should:

- Be an experimentally oriented study where measurements are made in representative flare systems, and where primary emphasis is given to obtaining closure of a mass balance accounting for all of the input fuel.
- Lead to an improved understanding of the mechanism by which the inefficiency, if any, arises in flare flames and the role played by coherent structures and intermittency in formation of pollutants.
- Generate information with regard to scale effects, since experimental work must be carried out at small scale and results translated to the population of industrial flares.
- Provide for the development and validation of a simple mode for the prediction of flare performance.
- Lead to an improved understanding of the factors which affect flare combustion, such that the effects of design and operational variables can be assessed.

The objective of this section is to propose an experimental program which provides for pilot scale measurements and the development and proof of experimental methods for the determination of flare combustion efficiency. Details of the proposed technical approach and an experimental plan are given below.

4.1 Overall Approach

The technical approach to the determination of flare efficiency must of necessity be one which involves the use of small or pilot scale experimental systems, for reasons mainly associated with cost and ease of operation. In this study an experimental program is proposed which requires the development of a pilot scale flare test facility designed specifically to allow the important aspects of scaling and data transfer to be addressed. The facility should allow for measurements on a number of different sized flare systems, where the scale relationship is properly defined and where designs and operating conditions are representative of commercial practice. The size of such an installation is an important consideration and must, in the final analysis, be a compromise between costs of operation and achievement of the desired experimental goals. A rationale for the selection of specific experimental flare sizes is discussed in a later section, where the use of 1½ inch, 3 inch, 6 inch and 12 inch nominal diameter flare heads is proposed. These systems should be exact scale replicas of each other so that geometrical relationships are precisely defined. Measurements may then be made on each system for a range of input and operating conditions which both cover the desired range for the study of parametric effects and allow predefined scaling approaches (e.g. constant velocity) to be investigated. Such measurements may then be extrapolated to hypothetical large scale flare systems with different dimensions and throughputs.

The approach taken in the detailed design of the flare heads should be one which results in the simplest construction possible, while characteristic features (e.g. flame holder, steam injection) of the large scale flare systems are retained. The choice of a simple configuration will better facilitate a more complete characterization of the system and the definition of scale relationships. Also the use of a basic flare system, without the use of sophisticated design appendages to improve efficiency, will permit the determination of combustion efficiency under potential worst-case conditions and allow investigation of the effect of more complicated design on combustion efficiency. Once a basic understanding of the controlling mechanisms has been achieved then the techniques may be developed for application to the quantification of the effects of operation and system design variables.

The measurement approach proposed is one in which initial effort is concentrated on a baseline condition using the smallest of the four experimental flare heads operating under quiescent ambient conditions. The objective here should be to develop first the measurement methodologies whereby efficiency can be quantified under well defined conditions, and where the time can be taken for the necessary detailed measurements without incurring prohibitive fuel costs. Detailed measurements should be made throughout the flare flame, and beyond the visible flame envelope, to determine profiles of temperature and species concentrations. In addition, measurements of tracer concentration should be made to determine dilution factors and local velocities and temperatures measured to permit integration of mass fluxes. The measurement and analysis methods employed should recognize the intermittent nature of flare flames and should make appropriate provisions for averaging and resolving fluctuations in the measurements. Since a primary objective of these measurements will be to develop information on the structure of these flames, conventional probing techniques must be used in conjunction with synchronized visualization techniques which permit individual eddies to be traced. Such techniques will involve the use of video recordings and high speed cinematography.

It is anticipated that a detailed measurement program as outlined above will provide the necessary information for an inproved understanding of combustion in flares, including the role played by eddies and intermittancy in the emissions of incompletely burned fuel. In addition, the measurements of local species concentration, temperature, and velocity will provide a means whereby local mass fluxes can be integrated to close a mass balance around the flare system. Mass balance closure is essential for the determination of combustion efficiency but has eluded many previous experimenters. For this reason an alternative method for integrating across the total flow must be applied, and in this plan the use of an exhaust hood to collect all combustion products is proposed. Since the hood itself may affect flare performance and efficiency, the errors introduced must be determined by the use of detailed measurements and visualization techniques made with and without the hood in place. This will also allow the relationship between local point measurements and overall efficiency to be determined. If successful, the use of the hood will permit a rapid screening of the effects of many variables, at least for the smallest of the flare systems and will allow reliable experimental techniques to be developed for application to larger scale systems.

Once the experimental techniques have been developed under well defined baseline conditions, less extensive measurements should be carried out to assess the effects of operating parameters and scale on flare performance. Operating parameters to be covered should include the use of steam, the effect of gas composition, gas throughput and the influence of ambient wind velocity. The extent to which detailed measurements are made should be reduced for tests on the larger size flares. In addition, a number of parametric studies should be carried out to determine the steam to gas ratio required for smokeless operation and the effects of throughput and gas composition on flame length at difference scales.

The above program will result in a series of detailed measurements and observations on flares for a range of scales and operating conditions. Such information may be extrapolated directly to comparable flares of larger size and used for the verification of existing scaling approaches. The relative effects of operating parameters and an improved understanding of the factors which affect flare inefficiency may then be used to estimate the emissions from flares of different designs. The data generated will also be available for the coincident development and validation of mathematical models of flare performance. It has been shown that existing flame models are not directly applicable to the flare problem but contain most of the required basic elements. A model should then be developed in which these elements are combined on the basis of experimental data.

In the following sections more detail concerning the development of the technical approach and the selection of design and operational variables are presented. These lead to the specification of requirements for a pilot scale flare test facility and a more detailed experimental plan.

4.2 The Need for Study of Pilot Scale Flares

Measurements on pilot scale flares are the only practical approach to determining the emission of incompletely burned fuel from flares, since only such systems can ensure:

- adequate control of input and ambient conditions
- facilitate accurate measurements
- low experimental costs.

Large scale flares, on the other hand, are difficult to isolate from the influence of uncontrolled atmospheric and plant conditions, difficult to sample from, and costs of operating them are generally prohibitive. By far the largest factor in determining the cost of a controlled experiment with such systems is the cost of fuel, and the use of pilot scale facilities are justified from this alone.

To be useful, data collected on pilot scale flare flames must be related to operation and performance of commercial flares. The current knowledge of scaling and modeling is insufficient for such a direct conversion. From an engineering and scientific point of view, however, pilot scale data is only useful to the extent it leads to:

- an improved understanding of flare emissions
- generalization of results on flares
- and allows the results to be transferred to large scale installations.

Unfortunately, very little information is available where results from pilot and large scale systems are compared. Very few detailed measurements have been made in large scale flares. Where scale comparison have been made, the data has been of a qualitative nature, mainly observations of flame length and form, with little supportive information concerning precise operating conditions. Such data has, however, been used in the development of scaling laws used to design industrial flares. However, these laws are not entirely satisfactory. More extensive work has been done on the enclosed combustion system. These studies have concluded that flames are difficult to scale and that it is impossible to simultaneously scale all aspects of the combustion process. The use of pilot scale facilities is, however, unavoidable in studying flares. Scaling laws are uncertain, and the experiments must be conducted in such a way that scale relationships can be empirically defined. In order to accomplish this, it is proposed to conduct measurements on four different sized flare systems, where the geometrical scale relationship is precisely defined. Use of scaling principals to design such a system is outlined below.

4.3 Size of Pilot Scale Flares

The selection of a size range for a pilot scale flare system is an important one and will be a compromise between the smallest size required to ensure that the data is representative and the largest size which has acceptable operating costs. From an engineering design point of view, flare manufacturers suggest that a flare head diameter in the range of 6 to 12 inches is the minimum size which is representative of the large elevated flares used in industry. A 12 inch diameter flare head burning propane diluted to 1000 Btu/ft^3, at a rate of 40 x 10^3 CFH (nozzle jet velocity of 14 feet/sec) will cost in excess of $300 per hour to operate in gas costs alone. (Experiments with CO and acetylene will cost 25 and 5 times more, respectively.) Therefore, it is recommended that a 12 inch diameter flare be considered as the maximum size for a pilot scale system. This size is comparable to small flares used in industry, and the operating cost is at the high limit of the program resources.

For the smallest size experimental flare, considerations are twofold: from a scientific standpoint, the flare should not be so small that the gas flows and resulting dimensionless groups which describe the flow field do not represent those of industrial flares; and from an engineering standpoint, construction of the system should be possible, while retaining all essential elements of the hardware. Based upon these considerations, an appropriate size for the small experimental flare would be of the order of 1½ inches diameter; this corresponds to the smallest size flare tip commercially available. The sizes recommended for the experimental flare system are therefore 1½, 3, 6 and 12 inches diameter and will allow a progression by a factor of two through the scale range. The 1½ inch tip will be used for detailed characterization of flares, while the 3-, 6- and 12-inch tips will produce flames more commensurate with industrial practice and will be used to develop information on the effects of scale.

The gas flow rates required for each of the flare sizes may then be selected to cover an appropriate range representative of industrial practice and to investigate the relative merits of various overall scaling approaches.

Operating conditions for the pilot scale flare should be selected based on the values of the groups in the hypothesized scaling laws. Values of these groups should be selected so that the results from the pilot scale studies can be extrapolated to commercial flares. Parameters which are important in the scaling of emissions from flares have been identified in Section 2.5.

From these considerations, it would appear that three composite scaling approaches are potentially applicable to flares and may be useful in defining the range of required gas flows for a study on pilot scale flares. These approaches are:

- Constant velocity
- Constant mean residence time
- Constant Richardson number

Scaling by constant velocity is the most commonly applied principle for scaling industrial flames, such as boiler burners. Boiler burners are sized by assuming constant velocity because a constant gas and air pressure are usually available. Constant velocity scaling requires that the exit velocity of gases at the flare tip be kept constant independent of scale and requires the gas throughput to vary as the square of the exit diameter. Commercial flare systems are scaled on this basis since designs are normally calculated on a constant exit Mach number for a given expected maximum flaring capacity. However, there is very little scientific justification for scaling by constant velocity. This technique does keep the flame within limits of flashback and blow off, but these limits are wide and more detailed scaling can be applied within the range.

In the constant mean residence time scaling approach, it is assumed that residence time within the flame volume is a determining parameter for overall similarity and that gas exit velocity must also vary with scale. This approach requires that gas throughput vary in proportion to the cube of the flare exit diameter. The discussion of models for eddy combustion in Section 2.5 concluded that constant residence time scaling is appropriate to scaling of flare flames.

Use of contant Richardson number has been successfully applied to flames and jets in which buoyancy is an important force (Ricou and Spalding, 1961, Becker and Yamazaki, 1978). Maintaining the flame Richardson number constant at different scales attempts to take into account the role of buoyancy in controlling the combustion process and allows for flame length dependence not only upon scale but also on gas velocity. For example, work carried out by Becker and Yamazaki (1978) shows a good correlation with this parameter.

Scaling by constant Richardson number results in a throughput to diameter relationship which lies midway between that of the velocity and residence time scaling.

The literature provides no firm proof that any of the above scaling approaches has any significant advantage, on the contrary, each is incomplete and potentially applicable only to special problems of limited interest. The use of such techniques provides, however, a means whereby gas throughput ranges can be selected for the different size flares, and a basis upon which experimental results can be compared and extrapolated to different systems. Table 4-1 presents a list of possible gas flow requirements for the 1½, 3, 6 and 12 inch flare systems proposed, which can be used as the basis for a test matrix. From the conditions within this table, cases 3, 6, 9 and 12 represent those where velocity is held constant; cases 1, 4, 7 and 10, those of constant mean residence time; and cases 2, 5, 8 and 11, those for constant Richardson number and cases 5 and 7 for constant Reynolds number.

The actual flare designs selected for the experimental program must produce combustion conditions which are representative of commercial flares. A summary of the hardware features of commercial flares has been presented in the background section, 2.0, of this report. With the exception of Coanda type nozzles, the majority of flare tips in use consist of a cylinderical exit terminated with a flame holder (see Appendix A). Such configurations are advantageous to this particular study where the emphasis in flare design should be upon simplicity so that the system may be characterized and scaled more easily.

Although the details of the experimental flare tip design are not yet finalized, it should consist of a cylindrical nozzle as shown conceptually in Figure 4-1. A propane-fired pilot at the edge of the nozzle exit insures ignition of the flare gas. A flame arrestor located near the end of the nozzle prevents flashback. These features satisfy the minimum requirements of a simple flare tip and are characteristic of "non-smokeless" or "utility" flares.

The plan should include experiments with steam injection to increase the fuel/air mixing. The injection configuration used in commercial flares varies in complexity from steam jets on the periphery of the tip to elaborate steam injectors distributed inside the tip. The experimental plan uses a removable

TABLE 4-1. EXPERIMENTAL PARAMETERS AND FUEL COSTS FOR PILOT SCALE FLARE TESTS

Dia. In.	Case	Velocity (Ft/Sec.)	Flow Rate (CFH)	$\tau = \frac{d_o}{V_o}$	Reynolds Number (d)	$g\frac{d}{u_o^2}$ Richardson Number	Propane Flow Rate (lb/hr) (a)	Propane Cost ($/hr)	Methane Flow Rate (lb/hr) (b)	Methane Cost ($/hr)	Nitrogen Flow Rate (lb/hr) (c)	Nitrogen Cost ($/hr)
1.5	1	0.25	11	500×10^{-3}	83	64.4	0.7	0.12	0.45	0.07	0.7	0.15
	2	1.41	62	89×10^{-3}	471	2.013	4.0	0.7	2.56	0.4	4.1	0.86
	3	10.0	442	13×10^{-3}	3343	0.0403	28	5.0	18.3	3.0	29.3	6.15
3.0	4	0.5	88	500×10^{-3}	334	32.20	5.6	1.0	3.64	0.6	5.8	1.2
	5	2.0	353	125×10^{-3}	1337	2.013	23	4.1	14.6	2.4	23.4	4.9
	6	10.0	1767	25×10^{-3}	6687	0.081	113	20.0	73.0	12.0	117.2	24.6
6.0	7	1.0	707	500×10^{-3}	1337	16.1	45	8.0	29.2	4.8	46.9	9.8
	8	2.83	2000	177×10^{-3}	3785	2.013	128	22.6	82.6	13.5	132.6	27.8
	9	10.0	7069	50×10^{-3}	13373	0.161	451	79.8	292.1	47.9	468.7	98.3
12.0	10	2.0	5655	500×10^{-3}	5349	8.05	361	63.8	233.7	38.8	375	78.6
	11	4.0	11310	250×10^{-3}	10699	2.013	722	127.7	467.7	76.6	750	157.3
	12	10.0	28274	100×10^{-3}	26747	0.322	1806	319.4	1168.0	191.4	1875	393

(a) Propane diluted to 1350 Btu/ft^3 (56 Volume %)

(b) Methane fired without dilution

(c) Nitrogen used to dilute propane to 175 Btu/ft^3 (92.7 volume %)

(d) Reynolds number based on 56% propane, 44% nitrogen mixture steam nozzle assembly on the periphery of the flare tip. This arrangement is flexible and permits a wide range of steam injection rates.

4.4 Operating Conditions

The choice of operating conditions for the experiment flare system should also meet requirements for scientific understanding of the process and the range of conditions actually encountered in practice. This study will concentrate on elevated flares which are widely used in all areas of industry and where the range of operating conditions is extremely diverse.

Flaring is basically an uncontrolled process, and the operating parameters which affect flare performance are:

- Flow rates - of gas, steam and air
- Gas properties - heating value, composition, H/C ratio
- Ambient conditions - temperature, wind, humidity, precipitation

The typical flow rates in elevated flares vary from velocities of less than one ft/sec to over 400 ft/sec under emergency flaring conditions. These vary high flow rates represent extreme conditions where the emphasis is on safe disposal of large quantities of gas rather than on ensuring clean and efficient combustion. In this study conditions of interest are those of continuous flaring where the flare is handling small quantities of gas which result mainly from leaks in valves in the process plant or of gases vented from storage tanks and process vessels. Under these conditions flare tip velocities are characteristically low, and the flare is operating at a small percentage of its design condition.

In the previous section, and shown in Table 4-1, a range of gas velocities and throughputs have been selected which satisfy the requirements for investigation of certain scaling criteria. These velocities represent a range which is believed to be typical of low and moderate load operation of flare systems and cover a range sufficiently wide to allow the effects of throughput to be investigated.

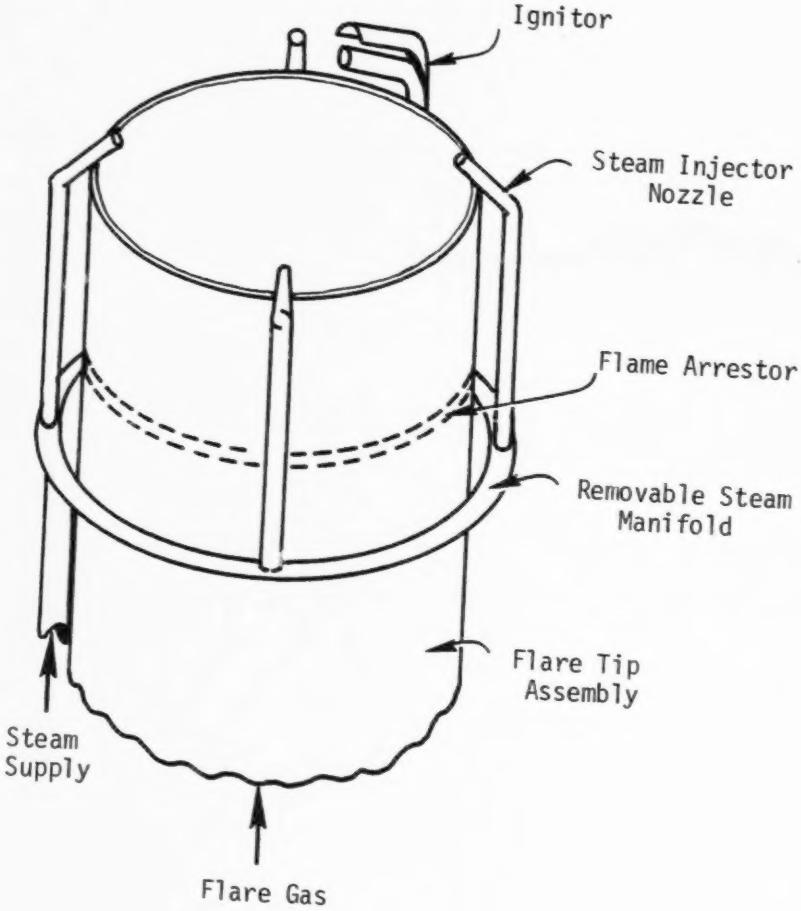

Ignitor
Steam Injector Nozzle
Flame Arrestor
Removable Steam Manifold
Flare Tip Assembly
Steam Supply
Flare Gas

Figure 4-1. Experimental flare tip concept.

4.5 Selection of Gases

The composition of the fuel also affects the performance of the flare flame. It affects the rate of burning, the flame temperature, flame buoyancy, and the mixing of air into the flame. With the exception of certain gases, such as NH_3 and H_2S, the fuels typically flared in industry fall into two classes. These are either hydrocarbons from coke ovens, refineries, oil production, and the chemical industry or inert gases plus carbon monoxide from blast furnaces. Some typical flare gas properties are listed in Section 2. Gases flared from blast furnaces account for 60 percent of the gases flared based on weight but only 19 percent of the gases based on heating value. Therefore, it is proposed that a mixed hydrocarbon fuel with a heating value from 1200 to 1500 Btu/ft^3 should be used for most experiments. This gas represents most gases of interest in flare performance. In the experimental program, this can most easily be achieved by blending propane (C_3H_8) with nitrogen.

While the flared gas calorific value is considered to be a primary parameter in determining flare efficiency (mainly through its effect on flame temperature), the gas composition itself as characterized by the H/C ratio is important for formation of soot. In order to investigate this effect, a limited series of measurements should be carried out with a gas having a different H/C ratio but the same calorific value. This can be achieved, for example, by substituting methane for some of the propane in the above mixture.

The low Btu, CO based gas from blast furnaces may be significantly harder to burn, easier to extinguish, and hence may produce greater amounts of unburned material (CO and others) than the flare gases that are mostly hydrocarbons. However, the cost of CO is high and experiments with CO are out of the scope of this study.

4.6 The Effect of Steam

In order to suppress soot formation, steam is most commonly injected into commercial flares and has the primary effect of enhancing fuel/air mixing at the root of the flame. Typical flare gas exit velocities range from 1 to 400 ft/sec, although in practice restrictions such as steam manifold size and steam capacity may limit the "smokeless" operating velocity to less than 100 ft/sec. The effect of injecting steam at different rates should, therefore, be investigated. For most cases, injecting steam at the minimum rate required to suppress smoke should be sufficient, since this is the level most often used in commercial flares. Steam injection need not, however, be the subject of detailed measurements for all conditions, and qualitative information can be obtained by observing the effect of steam/gas injection rate on flame length and luminosity for different flow rates and different scales.

4.7 The Effect of Wind

Except for wind, the effects of atmospheric conditions are not controllable within the scope of an experimental program. Elevated flares are exposed to varying crosswinds and these winds will affect the performance of the flare (Brzustowski, 1977). Consequently, the effects of a controlled crosswind should be investigated at conditions where the wind enhances mixing and at conditions where the wind no longer enhances mixing. Wind velocities between 0 and 14 mph will cover the most frequent atmospheric conditions. Air temperature and humidity should be recorded as part of the standard data. However, experiments need not be run in rain or other abnormal conditions.

4.8 Experimental Measurements

In this study, primary emphasis should be placed upon the elimination of the experimental errors associated with previous programs and on the verifications of the accuracy of the experimental measurements. Previous sections have identified the kinds of measurements required, and these will include:

- Probe measurements for the determination of local species and soot concentrations.
- Measurements of gas temperature and velocity.
- The use of a tracer to determine dilution factors.
- Visualization techniques such as photography, video and high-speed cinematography.

The objective of the measurement techniques should be to provide sufficient information so that a species mass balance can be closed and global combustion efficiencies can be determined as well as to provide an improved understanding of the role played by eddy processes in flare flame combustion.

In measurement of flare flames, a heavy reliance should be placed upon probe sampling for the determination of species concentration. In any future study, sampling times must be sufficiently long to determine the average mass flux of all species. This will require that velocity, concentration and temperature be measured simultaneously and for sufficiently long times such that the averaged values no longer change.

The concentration of all incompletely burned species (CO, HC, and soot) must be measured over a large enough area and with high enough sensitivity to preclude the escape of significant amounts of unburned material. Typical concentrations of 1 - 30 ppm hydrocarbons and CO and 1 - 10 mg/m^3 soot were identified as significant in Section 2. In future studies, gases should be measured to define the area of the plane over which concentrations should be measured.

Once the mass fluxes have been determined over the sampling plane, they must be properly integrated. Techniques to integrate the mass fluxes into an overall efficiency have been discussed in Section 2. Firstly, the average mass flux of material from the flame should be integrated over the plane, not the product of the average velocity, density, and concentration. Secondly, the use of a tracer which diffuses at the same rate as the product gas will allow the dilution factor to be accurately known. Helium is inappropriate for this purpose because of its high diffusion velocity. Sulfur dioxide is a likely candidate. It is relatively unchanged by combustion processes. If SO_2 is converted to other compounds, the effluent total sulfur can be analyzed by gas chromatographic techniques to give equivalent SO_2 values for the mass balance calculations.

If the multi-point mass flux measurements are accurate, the exiting carbon will be equal to the incoming carbon. However, mass fluxes computed from multi-point sampling is subject to errors caused by concentration, velocity and temperature measurements and the integration procedure. These deficiencies may be supplemented by the independent determination of mass fluxes of incompletely burned materials through the exhaust duct of a sample collection hood. This method of closing the material balance is far easier and more accurate. It eliminates the inaccuracies of velocity and temperature measurements and the error associated with integration. However, it is subject to the potential error that it may distort the flame. The magnitude of any distortion due to the hood can be determined by photographing the flame with and without the hood.

Also, any distortion of the flame will change the concentration, velocity and temperature measured by the probes positioned in the flow field of the flame. The early experiments will have to determine the methodology of multipoint and hood sampling.

In addition to direct probe sampling, it is recommended that within this experimental program the opportunity should be taken to further evaluate remote optical measuring techniques. Such techniques are not at present capable of providing data from which total mass balances, hence overall efficiency, can be estimated. The techniques do, however, offer the possibility for remote measurement on large industrial flares, particularly if a means of interpreting the measured data to characterize flare performance is available.

The selection of appropriate sampling and analytical techniques for an experimental program on flares is not a trivial problem. For this reason, a detailed discussion on measurement techniques is included separately as Section 5 of this report, and the required data quality assurance procedures are covered in Appendix C.

4.9 Modeling the Emission of Pollutants from Flares

A model of emissions of hydrocarbons and combustion products from flares must be developed and used to identify the operating and design parameters which most affect those emissions. The model is also required to extrapolate the measurements of emissions of unburned fuel on pilot scale flares to commercial flares. Without this, total and local emissions cannot be estimated.

Available models and scaling principles potentially applicable to flares were reviewed in Section 2.5. All previous scaling and modeling activities were found to be inapplicable to the problem of estimating emissions of incompletely burned fuel from flare flames. However, based on the work of Salvi and Payne (1980), Becker and Yamazaki, Brzustowski, and work done at EER, promising scaling parameters were selected: Constant nozzle velocity, constant residence time and Richardson number. The measurements of incompletely burned hydrocarbons are therefore required to provide data for a range of different flames with these values held constant. A design of one such set of experiments was shown in Table 4-1.

In order to supplement this type of information, more complicated modeling of flares is also needed. Unfortunately, most existing models are not applicable to flares, or probably to any large turbulent system. Fortunately, a new model of turbulent combustion, which accounts for the behavior of large eddies, is being developed at Caltech under a subcontract to EER as part of the EPA's FCR program.

This model, summarized in Section 2.5.5, may be used initially to guide and verify scaling principles, and as an aid to the interpretation and understanding of the experimental data. The data generated by the experimental program will, however, contribute also to the development of the model, particularly in the areas of macroscale entrainment and eddy formation and breakup. The program development approach should then utilize the family of computer programs developed for the analysis of turbulent diffusion flames, which include codes for confined flames with hot product recirculation and for unconfined flames. New data may then be incorporated into sub-elements of the model with varying degrees of sophistication, to describe macroscale entrainment, eddy breakup, flame reprocessing of products, dilution, microscale flamelets, finite rate chemical behavior and radiation.

4.10 Experimental Plan

In this section it is intended to outline the basic requirements of an experimental flare test program. This follows from the discussion of the technical approach presented in previous sections, and falls logically into two parts: A statement of the required scope of the pilot scale test facility, and a description of an experimental program.

4.10.1 Required Scope of the Pilot Scale Test Facility

In order to carry out an experimental test program a pilot scale facility is required which should incorporate certain features. The facility should provide for the control of the following independent parameters:

- Flare nozzle size: 1-1/2", 3", 6" and 12" nominal diameter.

- Fuel properties: Variable heating value and H/C ratio by blending propane, methane and nitrogen.
- Flare gas velocity: 0.25 to 10 ft/sec.
- Wind velocity: 0 to 14 mph (20 ft/sec).
- Steam injection rates: 0 to 1.0 lb/steam/lb of combustible.

The facility will then comprise a number of sub-systems, the most important of which are:

- Flare stack and tips.
- Fuel supply and handling (propane, methane, nitrogen).
- Tracer supply and handling (SO_2).
- Steam supply and handling.
- Flow controls and metering.
- Extractive species sampling systems capable of moving vertically and horizontally.
- An adjustable/removable sampling hood.
- Photography.
- Ambient conditions control: Wind generator and wind shield.
- Support structure for probes and auxiliary systems.
- Optical species sampling (in cooperation with the EPA measurement group).
- Data acquisition and processing.

The details of the experimental system will be discussed in Section 7.

4.10.2 Experimental Program

Based upon the foregoing discussion, an outline experimental program is proposed which is designed to address the key issues in the definition of flare efficiency and which will provide useful data at all stages of program development. The execution of the test program will be based upon a test matrix which identifies the conditions at which measurements are required to be made. The basic flare test matrix is presented in Table 4-2 and identifies a series of conditions which are valid for each of the 1-1/2, 3, 6, and 12 inch diameter experimental flare tips. The variable parameters covered are:

- Gas velocity: 3 levels for each flare tip size.
- Gas composition: 3 different gas mixtures (2 having a calorific value of 1000 Btu/ft^3 and made up from mixtures of C_3H_8 and N_2, and C_3H_8, CH_4 and N_2 respectively, and one of a lower calorific value made up from CH_4, C_3H_8 and N_2).
- Steam.
- Wind velocity.
- Flare size: 1-1/2, 3, 6 and 12 inch diameter.

The levels of velocity proposed for each of the different flares are those identified in Table 4-1. The rationale for the selection of certain parameters has been covered in previous sections. The test matrix attempts not to be overly ambitious, but to concentrate on a limited range of key variables and conditions which might be easily characterized. In the execution of the test program, every attempt should be made to carry out sampling under quiescent wind conditions. This can be achieved by careful location of the test facility, the use of wind screens where appropriate, and by carrying out measurements during calm periods.

The execution of the test program should be divided into four tasks, each of which can be regarded as a separate entity designed to provide information necessary to define the approach to be used in continuation of the program.

Task 1

Task 1 of the program is intended as a parameter screening study, where the measurements taken are minimal but each of the proposed test conditions is investigated. Measurements taken will be mainly original records of flame length and form, supplemented by limited still photography and video recordings of the different flames. The objective of the tests will be to provide information on the effects of gas flow rate, steam rate, gas composition and

TABLE 4-2. BASIC FLARE TEST MATRIX

#	SET	VARIABLE	VELOCITY			GAS COMPOSITION CALORIFIC VALUE			STEAM		WIND		HOOD †	
			1	2	3	Low	Hi 1	Hi 2	On	* Off	On	Off	Yes	No
1	1	Base Case No Hood		X			X			X				X
2	1	Base Case Hood		X			X			X		X	X	
3	1	With Steam		X			X		X			X	X	X
4	1	Add Wind		X			X			X	X			X
5	1	Low Btu		X		X				X			X	X
6	1	Alternate Gas H/C		X				X		X		X	X	X
7	2	Low Re	X				X			X		X	X	X
8	2	High Re			X		X			X		X	X	X
9	3		Selected parameters based on previous test results.											
10	3													

* = To be decided on the basis of initial observations. If flames are not representative then threshold steam flow for "smokeless" operation should be used.

† = The use of the hood will depend upon the experience gained in test conditions #1 and 2

flare size on flame characteristics.

This task will thus provide the basic information to assess operation of the pilot scale system and to ensure that the flare flames exhibit the required representative features. The data generated should be evaluated in terms of available models for flare combustion and for the predicted effects of scale. If necessary, the experimental plan may be re-evaluated and altered to more appropriate experimental conditions.

Task 2

This experimental task will be concerned primarily with the development and verification of measurement techniques. Attention here will be focused on the small 1-1/2 inch diameter flare tip and the nominal baseline conditions 1 and 2 in Table 4-2. In these tests, a series of very detailed measurements will be made both within the flare flame and beyond the visible flame envelope. These measurements will consist primarily of probe measurements in the flame axial and radial directions. The primary measurements required are:

- Continuous and integrated sampling for C_xH_y, CO, CO_2, O_2.
- Tracer gas concentration.
- Temperature.
- Soot concentration.

These measurements will be supplemented by synchronized video tape recordings, still photography and high speed cinematography. The details of the actual measurement techniques to be used are presented in Section 7. These measurements will be made both with and without the sampling hood in place, so that the use of this technique as a means for integrating the effluent may be evaluated.

In the evaluation of the data, the detailed local measurements must be integrated across a plane to obtain a mass balance across the flare to determine the overall efficiency. This is seen as perhaps the most critical and time consuming phase of the work. The detailed measurement data must be further inspected and evaluated to provide information with regard to the structure of the flare flames and the role played by eddy formation, quenching and intermittency.

This task will result in the definition of the level and extent of sampling required in order to characterize a flare flame. Together with an improved understanding of the flare combustion process, this should lead to an identification of the minimum measurement program required to determine flare efficiency.

Task 3

Using the measurement methodologies developed in Phase 2 of the experimental program, Task 3 will involve the application of these techniques to the remainder of the test conditions. Testing on the small, 1-1/2 inch diameter flare will be concluded first before progressing to the 3, 6, and 12 inch diameter systems. It is anticipated that as the experiment proceeds to the larger flares and higher flow rates, the degree of sophistication in the measurements and the number of conditions investigated in detail will be reduced. The extent to which detailed measurements are made in the larger flares will depend primarily on cost factors, and the selection of conditions for detailed investigation will be based upon experience gained in earlier stages of the experimental program.

Task 4

This part of the program is intended as a general task which provides for the evaluation of the test data in its entirety, the development and validation of a mathematical modeling and scaling approach. Documentation of the study will include technical papers, presentations, and a comprehensive final report.

5.0 FACILITIES REVIEW

This section reviews the characteristics of a flare system necessary to insure that the results from these tests are useful. It evaluates the extent to which existing facilities fulfill these needs. Previous data on flares is, at best, fragmentary and uncertain, because accurate measurements of these flames are extremely difficult. Pilot-scale tests facilities designed specifically to determine the extent and mechanism of emissions from flames appear to be the most cost effective solution.

A limited number of flare test facilities exist. However, none of these facilities are fully satisfactory, nor could they be easily modified for the EPA study of emissions from flares. Therefore, an EPA-owned flare test facility has been designed specifically to determine the extent of emissions from flares.

5.1 Facility Requirements

A facility must meet a number of criteria if emissions from flares are to be adequately determined:

- The conditions of operating flares must either be simulated or properly scaled so that the results can be translated to the population of industrial flares.
- The parameters which affect the performance of flares must be controlled.
- The facility must be designed so that accurate measurements can be made.
- The facility must be easy and inexpensive to operate.
- The EPA and all interested parties must have full control of the facility and full access to the data from the facility.

Simulated Flare

Previous studies of flares have concluded that accurate measurement of emissions cannot be made on large-scale flares. Therefore, the system design must simulate the following conditions of industrial flares:

- Gases flared must represent those flared in industrial operations.

- The flare must be designed to cover the wide range of nozzle velocities used in industrial flares.
- The facilities must include provisions to determine the effect of steam injection on flare performance.

The gases used in the test facilities must represent large classes of gases flared in industries. The two major classes of gases flared in industry were indentified earlier in this report. This program will concentrate on hydrocarbon fuels with heating values of about 1200 to 1500 Btu/scf and 150 to 200 Btu/scf which are representative of fuels flared in petroleum production, petroleum refineries, the chemical industry, and coke oven operations. The hydrogen-to-carbon ratio of this gas should be varied to represent industrial gases and will affect the performance of the flare.

These gases will need to be mixed and supplied steadily in large amounts to the experimental flare. The hydrocarbon gases can be mixed from stored components of propane, methane and nitrogen. The largest flow rate of gas anticipated for the experimental conditions is about 28,000 ft^3/hr. Facilities must therefore be available to store, meter, and mix this large quantity of fuel. The capability of mixing a third gas must also be available so that the hydrogen-to-carbon ratio can be altered.

The experimental flare must be capable of operating over the high gas velocities and the wide turn-down ratios used in industry. The maximum nozzle velocity used during industrial emergencies may be 600 ft/sec and the lowest velocity may be 0.15 ft/sec. The conditions listed in Table 4-1 will cover the important range of velocities used in industrial flaring. Ignition must remain stable over this range of velocities. This will require that the pilot-scale facility use pilot flame stabilization as discussed in Section 7.

Steam is typically injected into flares to suppress soot. Provisions to simulate steam injection must be included in the pilot-scale facility. The industry typically injects about 0.5 steam/lb of fuel. However, the optimum level of steam injection may be higher and the facilities should be available in inject steam at levels up to 1 lb steam/lb of fuel. For the high flow rates, this would require about 200 lb steam/hr. The low flow rate of steam would require only about 10 lb of steam/hr.

The method of steam injection should also simulate industrial practice. Steam is most often injected from the periphery of the flare head and the optimum directions of injections intersect at the center at 60° to the vertical. Consequently, the steam injection configuration discussed in Section 7 represents common industrial practice.

Wind conditions must be simulated in an experimental pilot-scale flare system so that the effect of wind conditions on flare performance can be determined. Typical winds are on the order of 0-14 mph. If required, these winds may be supplied with a large blower as discussed in Section 7. The blower will require approximately 100 hp to supply 14 mph wind.

Scaled Properties

The properties of the flare that are not simulated must be scaled so that the results of the pilot-scale studies can be applied to the population of industrial flares. Unfortunately, the important scaling parameters for flare flames are unknown. Therefore, the pilot-scale flare facility design must be flexible enough so that different potential scaling strategies can be investigated.

Three parameters are proposed in scaling flares:

- Constant Nozzle Velocity
- Constant Residence Time
- Constant Richardson Number

Constant nozzle velocity is typically used to scale industrial flares. However, scaling by constant residence time appeared to be a better approach to scaling boiler flames in a study conducted at the International Flame Research Foundation (IFRF). Finally, use of constant Richardson number has successfully scaled small buoyant flames. The pilot-scale facility should be capable of investigating all three approaches over the industrial range of operational and design parameters. An example of such conditions are shown in Table 4-1.

Control of the Flare Flame

Input parameters which affect the performance of the flare must be controlled if accurate measurements are to be made. The parameters which need to be controlled are the flow rate and composition of the fuel, the flow rate and conditions of the steam, and the wind velocity passing the flare.

The composition of the fuel must be controlled so that the heating value does not vary by more than 5 percent and the hydrogen-to-carbon ratio does not vary by more than 3 percent. These accuracies can be accomplished by using careful but standard metering and mixing techniques. The overall flow rate of the fuel should be controlled to about 3 percent. This can again be achieved by careful standard metering techniques.

Steam pressure and flow rate should be controlled to within about 10 percent. This is quite easy to accomplish with standard pressure control and metering devices.

The wind velocity needs to be controlled to within about 10 percent. To achieve this level, external wind must be measured and/or the flare protected from the atmosphere. This can be accomplished by the use of screens. Artificially generated wind may be controlled by measuring the flow and venting some air from the blower discharge duct.

Accurate Measurements

The facility should be designed so that measurements can be easily and accurately made. The flare flame must be large enough so that the results can be scaled, but small enough so that accurate measurements can be made. Additional facilities such as a hood and delivery of a tracer should be provided to improve the accuracy of the measurements.

Large flames are inherently difficult and dangerous to sample. The longest flame expected in a study of pilot-scale flares may be 30 feet. This would require that a multi-tipped probe be accurately positioned some 60 feet above the ground. The probe must be positioned and remain stable to within several inches. This will require a movable scaffold which can be positioned accurately.

Use of a hood to capture the effluent from a flare flame will greatly improve the accuracy with which emissions can be measured. The hood must be wide enough to capture all the effluent and must be mounted so the vertical position of the hood can be positioned above the flame far enough so as not to disturb the flame, but not so far that the exhaust products escape or are diluted below the detection limit of the analytical equipment.

Use of a tracer can also improve the accuracy of local efficiencies which can be measured without the inherently inaccurate local velocities measurements. The tracer, however, must be delivered at an accuracy of better than 1 percent and measured at a level of 1-10 ppm with an accuracy of better than 1 percent. Typically, such accuracy can be achieved only by sonic flow critical orifices. Sulfur dioxide can be measured at these low levels within the specified accuracy.

The concentration of all emissions from the flame must be accurately measured. The emissions, techniques to measure them, and the accuracy of the measurements are discussed in Section 7. Typically, compounds must be measured within an accuracy of about 10 ppm or 10 mg/m^3.

The facility should also be capable of monitoring the appearance and behavior of the flame. The flame should be monitored continuously with a spatial resolution of several inches and a time resolution of several milliseconds.

Operation of the Facility

The facility should be easy and inexpensive to operate and yet simulate actual flare conditions. The size of the flame largely determines the extent to which industrial conditions are simulated. It also determines the expense and ease of operation of the system.

Flare tips used in the experimental facility should be within the size range of commercial flares. Most commercial flare tips range from 16 inches to 6 feet in diameter. However, commercial flares are available from 1½ inches to 12 feet in diameter. Flare tips should be selected which are large enough to be within the commercial range, but small enough to produce manageable flames inexpensively. Flare tips the size of small-size industrial tips should be used in the experimental facility. These tips should be as small as possible but consistent with developing an adequate range of scaling parameters. Table 4-1 indicates that four flare sizes (1½-, 3-, 6-, and 12-inch) fulfill these criteria.

5.2 Existing Facilities

A limited number of potential flare test facilities exist, but each of these has limitations when considered for an EPA study of emissions from flare flames.

Although several facilities exist in Western Europe, such as International Flame Research Foundation (Holland) and Oberrheinischen Mineralöliwerke GMBH (W. Germany, where Siegel did his research), they will not be considered further primarily because of the high costs associated with personnel travel. Their use could present other problems such as the language barrier, protracted contractual arrangements, and mail and phone communication lags over long distance. All these would impede the timely execution of this research program.

Among the the American facilities, those owned and used by flare equipment manufacturers would seem most appropriate. The facility at John Zink Company (Tulsa, Oklahoma) is reputed to be the largest and most suitable for long term flare testing.

Although the Zink facility has the basic characteristics for study of flare flame emissions, several improvements and additions would have to be provided to satisfy the present requirements:

- A means of providing and accurately measuring tracer flow.
- Construction and operation of a hood.
- Control and measurement of wind parameters.
- Improved choice of fuels available and means for accurate dilution and delivery.
- Means for accurate placement of sampling devices with required spatial and measurement resolution.
- Assembly of complete portable gas and solids sampling system and analysis equipment.

Wind control would be especially difficult at the Zink facility because of the limited space in the crowded test facility. There are too many nearby combustion sources and structures which may affect the measurements of the flare flame.

In addition to these hardware requirements, there would be extensive costs associated with project personnel on temporary duty at the Zink facility. Based on three separate test sessions totaling 4 months duration, the cost of transportation, lodging and per diem for a 2-person team is estimated to cost the contract $19,500, directly.

While the John Zink Company has offered use of their facility for this program, access to and control of experimental set-up variables would be limited. This research can only be successful if the research team has direct control over all variables, the facility is continuously available and if raw operating data is instantly accessable. The facility must be dedicated to this project to achieve the project goals within the designated time. It is concluded that these factors, namely, extensive facility upgrade, high costs of personnel on temporary duty and ease of accessibility and control preclude using the Zink facility.

Other existing facilities that might be appropriate for this project are: the facility at National Air Oil Burner in Philadelphia; the Institute for Gas Technology in Chicago. However, these candidates are subject to varying degrees of the above cost factors. Furthermore, these alternate facilities would not be as effective as the John Zink facility and so are not considered further.

5.3 Proposed Flare Facility

Based on the above considerations, it is proposed that an EPA-owned flare facility be built to meet the program goals. The proposed facility would have the advantage of being dedicated both in design and operation to this program and would provide the main features for:

- Precise control of flare input variables for repeatability.
- Ease of access to the flare(s) for both continuous sampling and the possibility for assessment/development of remote measurement systems.
- Flexibility in size and operating conditions to verify scaling approaches for a high confidence level in the assessment of full-scale systems.

The remainder of this report presents a proposed design for the EPA-owned flare facility to be located at the EER El Toro test site. The facility will have the characteristics to meet program needs outlined in Section 4.10. Several favorable aspects to this approach can be noted. EER is an independent, research-oriented company experienced in measurements on large-scale combustion systems. As a result of other EPA programs at EER, several pieces of EPA-owned equipment are available as needed. The test site is located in a region where "high technology" services are locally available. Also, results of ongoing fundamental research on large turbulent flame phenomena will be available to aid in interpretation of the flare test data.

6.0 DESIGN OBJECTIVES

A review of research facilities, as discussed in Section 5, indicates that existing facilities are not fully satisfactory for meeting the program objectives. The purpose of this design effort is to study the requirements of the flare tests and their operations and to arrive at a description of a test facility that fulfills these requirements.

6.1 Design Criteria

Flaring in an industrial environment is a process that is affected by a complex array of variables, many of which are uncontrolled. In order to determine the different effects of the many parameters, the flare test facility must produce flare flames that exhibit features representative of industrial flares. It must also be able to control the input parameters within acceptable limits and allow accurate measurements of the output dependent parameters. Yet, the facility has to be sufficiently simple so that the data generated may be understood, generalized and applied to other flares. Also, the design has to consider the capital and operating costs and maximize the results with the available resources.

6.2 Approach

Instead of trying to duplicate all the varieties of hardware and fuels used in the industry, the test facility will simulate the important features of the flare process. The objective of the design is not to build an optimized flare tip in terms of combustion efficiency and steam utilization, but rather to include sufficient flexibility to simulate the flaring process so that the measurements can describe flare flame characteristics. The experimental flare system discussed herein is based on flare heads which retain all the important features but are scaled down in size. An array of different size flare heads will provide information on the effects and parameters of scale.

6.3 Parameters

The parameters that are fundamental to the design are:

- Flare Size
- Flare Gas Properties
- Nozzle Gas Exit Velocity

- Wind Condition
- Air Entrainment
- Measurements

6.3.1 Flare Size

Since flares produce jet diffusion flames, the size of the jet is an important parameter. Typical industrial flare sizes range from 1½ inches to over 60 inches in diameter. Although it is desirable to test flares that cover the full size range, the high costs and the difficulty associated with measuring the large flare flames limit the practicable tests to flares no larger than 24 inches. Even a 12-inch flare running at 2 ft/sec exit velocity will consume about 7500 ft^3/hr of gas. Therefore, the proposed flare sizes are 1½, 3, 6, and 12 inches. With the 12-inch flare, a limited number of tests must be run at reduced-nozzle gas velocities.

6.3.2 Flare Gas Properties

The important flare gas properties are the H/C ratio and the heating value. As discussed in the earlier report, four flare gases will be tested and will simulate the gases flared in refineries and petrochemical plants.

- Propane diluted by nitrogen to give H/C of 2.67 and a heating value of 1350 Btu/ft^3.
- Propane diluted by nitrogen to a heating value of about 175 Btu/ft^3.
- Methane gas with H/C of 4.0 and heating value of 1000 Btu/ft^3.
- A methane nitrogen mixture with a heating value of about 175 Btu/ft^3.

If warranted, other gas compositions can be prepared and studied.

6.3.3 Nozzle Exit Velocity

One accepted guideline used in flare design is to limit the maximum anticipated gas exit velocity to 20 percent of the sonic velocity. This corresponds to about 225 ft/sec, although gases have been flared at 500 ft/sec during emergencies. The proposed tests will cover the gas velocities from 0.25 to 10 ft/sec.

6.3.4 Wind Conditions

The flare flame will be studied under at least three wind conditions: quiescent, 7 and 14 mph. Since the natural wind conditions are unpredictable and uncontrolled, means have to be included to minimize the impact of the natural wind on the flare flame during the controlled wind experiments. Experiments under natural wind conditions will be limited to photographic characterization of the flame. These photographic records will be used to compare with those taken under controlled wind conditions.

6.3.5 Air Entrainment

Two air entrainment methods will be studied:

- Natural convection - uncontrolled.
- Steam injection: 0-1 lb steam/lb fuel.

The amount of steam injection will be varied pursuant to the sooting behavior of the flare and the program goals.

6.3.6 Measurements

The measurements will include input and output variables which are needed to define the flare operational conditions and resultant combustion and destruction efficiency. The measurements are:

- fuel and steam flow rates
- ambient conditions: wind, temperature and humidity
- species concentration in and above flame
- temperature and velocity in and above flame
- flame forms and structures.

6.4 Facility Capability

The success of the flare experiments depend on the design of the facility. The key features of the proposed facility are discussed in the following:

- Experiments will be run using different size flare heads: 1½, 3, 6, and 12 inches in diameter. Experiments with larger flare heads can be supported, but at reduced nozzle gas velocities and shorter run times. These sizes have been selected so that the flames can be controlled and measured. The larger sizes will produce data more commensurate with industrial flares.
- A fuel system will accurately meter and blend up to three gases to

provide a flare gas with the desired composition over a wide range of flow rates. Propane, methane and nitrogen can be blended to simulate the gases flared in refineries, petrochemical plants, and coke ovens.

- Flow controls will meter addition/injection of steam. Steam is the most common means to suppress smoking in flares and is usually the only control available to the operator.
- Use of a tracer gas will determine dilution by entrained air. The dilution by air directly affects the computation of efficiency and has to be determined to insure accuracy in mass flux measurements.
- Wind screens and a wind generator will produce a controlled environment so that flare flames may be reproduced under conditions specified in the test matrix. Experiments under natural wind conditions are difficult to quantify. Unless extractive measurements methods are developed and proven to produce useable data, the flames under natural wind conditions will be analyzed by photographic techniques only.
- Complete instrumentation will measure local concentrations, temperatures and velocities so that local material fluxes may be determined.
- The use of a sample hood will provide a means to confirm the multipoint measurements. If use of the hood is successful, it can also greatly reduce the experimental time during screening and exploratory tests.
- Photography will produce records of the global and local flame structures so that these may be correlated with the emissions.
- Control and data recording hardware will reduce operation manpower and improve data quality and assure completeness of the data.

These features have been specified following careful study of the research objectives. A conceptual design of the test facility has been developed and will be discussed in the next section.

7.0 FACILITY DESIGN

The following sections will discuss the design of the various subsystems:

- Flare stack and tips.
- Fuel supply and handling (propane, methane, nitrogen and/or CO_2).
- Tracer supply and handling (SO_2).
- Steam supply.
- Flow controls and metering.
- Ambient conditions measurement and control.
- Extractive species sampling.
- Photography.
- Control, data acquisition and processing.

7.1 Flare Stack and Flare Tip

The flare stack serves several purposes. Gas flows through the stack to the tip where it is ignited and burned. The stack also supports and positions the flare tip at a safe elevation above grade. In some systems, the flare stack may incorporate flame arrestors, gas seals, and liquid knock-out chambers. The design considerations are structural strength, flow capacity, the maximum radiation to grade and surrounding equipment and prevention of flame propagation back into the piping system.

As discussed in the test plan, a minimum of four flare sizes will be studied, namely 1½, 3, 6, and 12 inches. These sizes were selected based on the research objectives and the constraints of capital and operating costs. The different size flares will reproduce data on the effects of scale. While the smaller sizes (1½ and 3 inches) will be studied more extensively because the experiments can be better controlled and cost substantially less, the 6-inch and 12-inch flares are needed to link the small-scale findings to larger-scale flares.

A nominal 6-inch diameter steel pipe will make up the stack for all the tips. This simplifies plumbing and eliminates duplication of flame arrestors and other auxiliary equipment. The stack will be designed so that each tip can be removed and installed with minimum effort. Furthermore, it is anticipated that the flare tips will be changed infrequently and will not cause excessive down-time and hinder progress of the experiments.

The literature (Oenbring and Sitterman, 1980) consistently suggests that 1500 Bt/hr-ft^2 of thermal radiation (including solar radiation) is the maximum allowable exposure for a normally clothed person. This constraint would put the experimental flare tip over 30 feet above ground. While industrial flaring is inherently an unscheduled event, the operating situation for the test facility is quite different in that the flaring tests are scheduled and are closely monitored. Therefore, all personnel can be cleared from the hazardous area before flaring commences. With this reduction in danger to personnel, the flare tip can then be lowered, provided the maximum radiation intensity is kept below the level that causes spontaneous ingnition of wood and other materials. Based on the National Fire Code which suggests 4000 Btu/hr-ft^2 as the maximum possible radiation level, the flare tip may be lowered to about 15 feet above-ground. At this height, the flare stack can be made of standard steel pipe and will be self-supporting.

A porous metal plug inserted inside the flare stack will act as a flame arrestor. This is absolutely essential to prevent the flame from flashing back into the fuel piping system. The flare stack will be mounted on a mobile platform so that the relative positions of the sample probes, the hood and the flare flame may be varied.

Two approaches for acquiring the flare tips have been considered: 1) purchase from manufacturers, and 2) fabrication by EER. While using commercial flare heads will ensure that the pilot-scale experiments include commercial design features, testing with commercial flare heads alone would not meet the project objectives for several reasons. First, the commercial designs are likely to be proprietary and release of such information in public records may infringe on the manufacturer's rights. Also, the commercial flare heads are designed using undisclosed scaling criteria. Interpretation of the data from flare heads of the same type but of different sizes will be difficult. Therefore, it becomes necessary for this program to use a simple flare head design that incorporates the prominent features of a steam-assisted flare which includes steam injectors, pilot, and flame arrestors. For the above stated reasons, the four flare tips to be used in the program will be constructed by

EER. The option of testing a commercial tip could also be considered, if it could be made available at minimal cost.

Figure 7-1 shows the design of the test flare heads. For the 6-inch flare, a schedule 40, 6-inch diameter stainless steel pipe forms the main body. The flare tip does not include flame retention, which is only needed at high nozzle velocities and the planned experiments will be run at 10 ft/sec or less. However, it includes a steam ring sized for 1000 lb/hr of 100 psig steam. The manifold is a torroidal ring made of 2-inch pipe and has an 8-inch ID. Steam is supplied to the steam ring via a 2-inch pipe. Eight ½-inch OD, stainless steel tubes rise from the manifold to form the steam injectors. They are bent to inject steam at a 60^0 angle relative to the vertical. The steam injectors have been designed to be as simple as possible so that established jet models may be used to estimate the air entrainment. The entire steam injector assembly is supported by stops welded on the outside of the 6-inch pipe. The assembly can be removed for tests that do not require steam injection. A single pilot near the flare tip will stabilize the flare flame.

The dimensions of the 1½-, 3-, 3- and 12-inch flare heads are scaled linearly, and are shown in Table 7-1. All flare tips will be 6 feet long and terminate with plate flanges that have drillings conforming to a 6-inch, 150 lb flange. This ensures easy changeover between flare tips.

7.2 Fuel Supply and Handling

The test plan inlcudes two fuel gases, namely, propane and methane. These will be blended with nitrogen and/or carbon dioxide to produce mixtures with the desired composition and heating value. The consumption of these gases depends directly on the flare size and the nozzle gas velocity. Figure 7-2 illustrates the relationship between total gas consumption rates, flare size and nozzle velocity. The fuel system has to satisfy the flow rate demand and also provide sufficient capacity for a complete test.

The maximum demand occurs when the large flare heads are operated at high nozzle velocities. As discussed in the test plan, this corresponds to the 12-inch flare tested at 10 ft/sec which will consume gas at about 28,000 ft^3/hr. Table 7-2 lists the specifications of the fuel supply system. Figure 7-3 is a flow schematic for the fuel supply systems. Propane will be stored as a

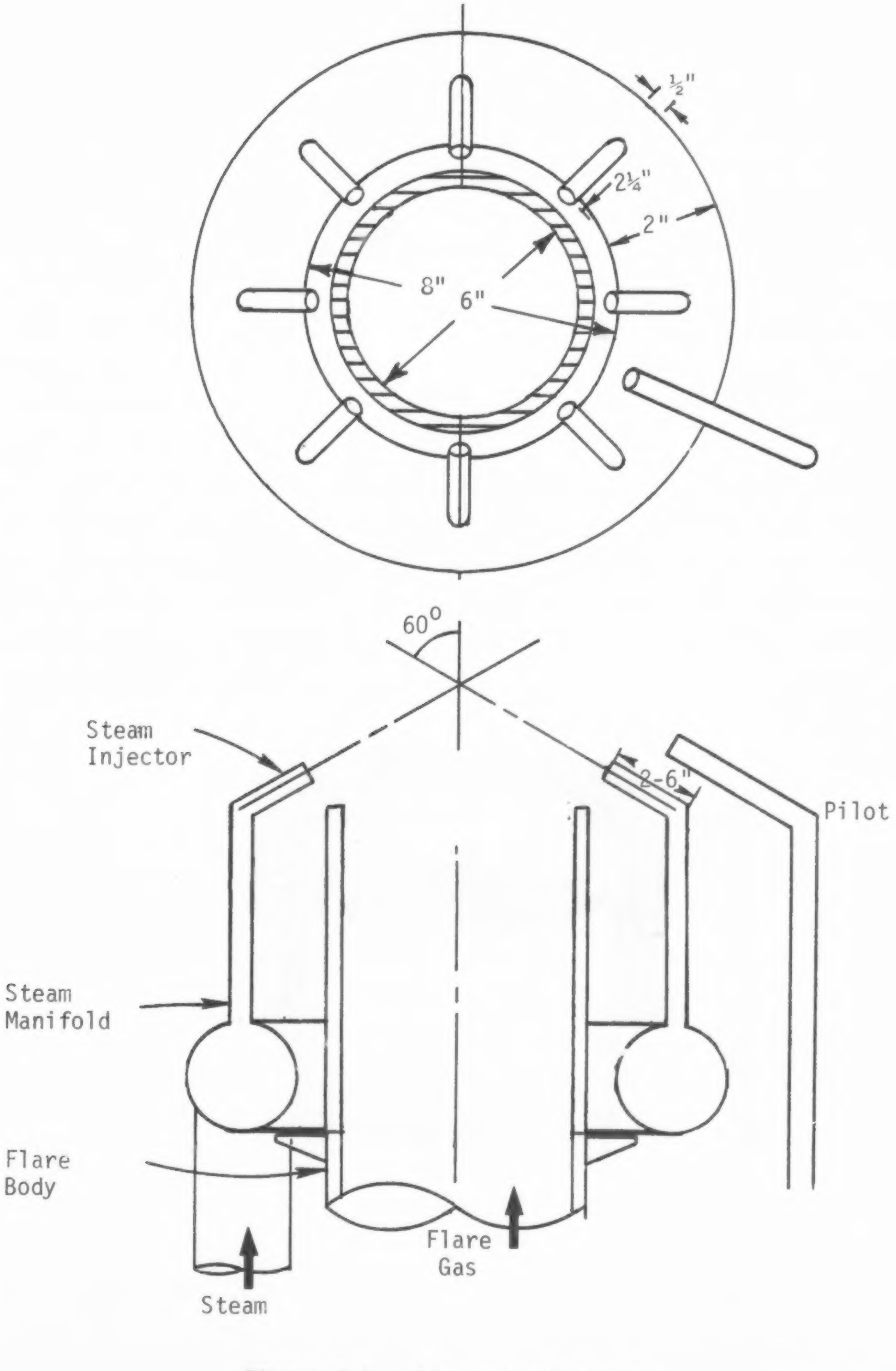

½"
2¼"
2"
8"
6"
60°
Steam Injector
2-6"
Pilot
Steam Manifold
Flare Body
Flare Gas
Steam

Figure 7-1. Six-inch flare head.

TABLE 7-1. FLARE HEAD DIMENSIONS

Nominal Flare Size (inc.)	1½"	3"	6"	12"
Flare Tip OD (in.)	1.900	3.500	6.625	12.750
Flare Tip ID (in.)	1.500	3.068	6.000	12.000
Steam Ring				
Channel ID (in.)	0.622	1.049	2.067	4.026
Channel OD (in.)	0.840	1.315	2.375	4.500
Torroid ID (in.)	2	4	8	16
No. of Steam Nozzles	8	8	8	8
Nozzle ID (in.)	0.093	0.186	0.372	0.744
Nozzle OD (in.)	0.125	0.250	0.500	1.000
Injection angle, degress	60	60	60	60

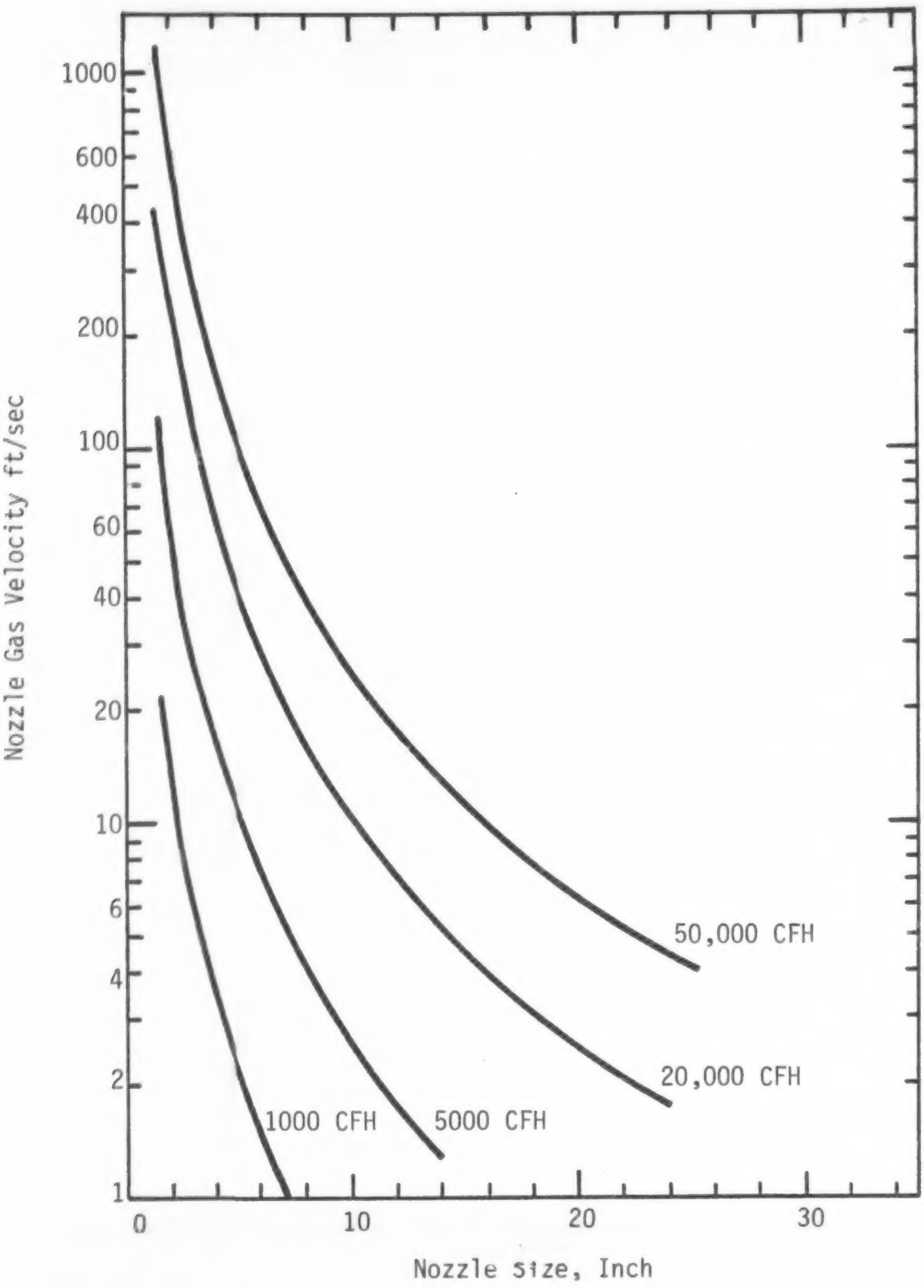


Figure 7-2. Gas consumption for different nozzle sizes and nozzle gas velocities.

TABLE 7-2. FUEL SUPPLY SPECIFICATIONS

	Propane	Methane (Natural Gas)	N_2	CO_2
Tank Capacity (cu. ft. of gas).	80,000	utility main	100,000	120,000
Discharge Capacity (cu. ft/hr)	30,000	30,000	48,000	48,000
Nominal Discharge Rate (cu. ft/hr)	3,000	3,000	4,800	4,800
Nominal Run Time (hrs)	26.7	-	20.1	25.0
Minimum Run Time (hrs)	2.5	-	2.1	2.5

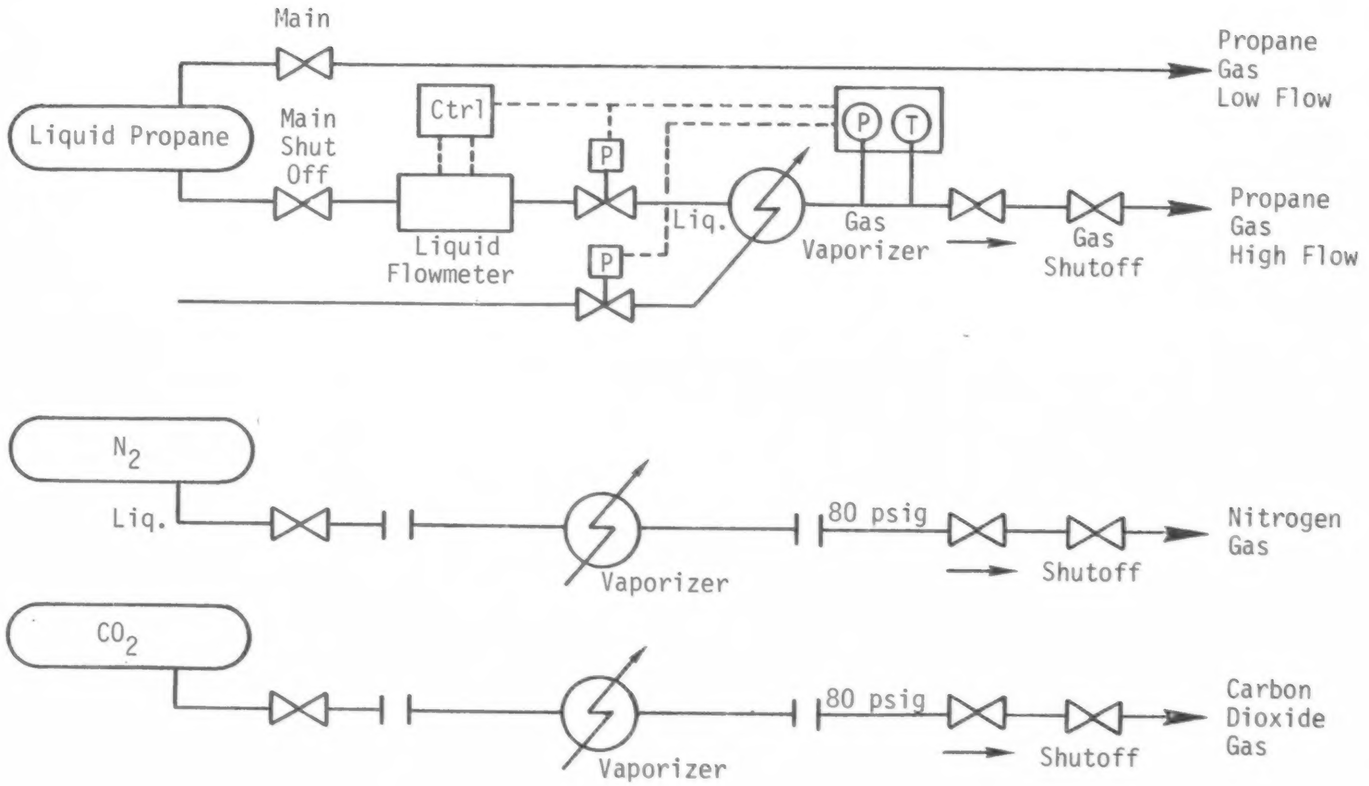

Main
Liquid Propane
Main
Shut
Off
Ctrl
Liquid
Flowmeter
P
P
Liq.
P
T
Gas
Vaporizer
Gas
Shutoff
Propane
Gas
Low Flow
Propane
Gas
High Flow
N_2
Liq.
Vaporizer
80 psig
Shutoff
Nitrogen
Gas
CO_2
Vaporizer
80 psig
Shutoff
Carbon
Dioxide
Gas

Figure 7-3. Fuel supply system.

liquid in a tank. The liquid propane will be transferred from the delivery truck on a regular basis. The nitrogen will be supplied as liquid.

The high flow rates for some tests necessitate the use of vaporizers to supply the energy of vaporization and expansion. The vaporizer for the propane system will be fixed installation and requires a maximum rate of about 1500 lb/hr of saturated steam. The vaporizers for the other gases will be leased from the gas supplier and installed on-site.

7.3 Tracer Supply

Sulfur dioxide will be used as a tracer. The amount of SO_2 needed depends on the sensitivity of the analytical instrument, anticipated air dilution and the ambient SO_2 concentration. The addition rate of the tracer has been based on 2 ppm SO_2 resolution in the sample system, local air dilution by 250 times the fuel volume and a target precision in dilution calculation of 5 percent. The calculations indicate that the SO_2 concentration in the fuel stream needs to be about 1 percent.

The calculated tracer use at these conditions for the planned experiments is shown in Table 7-3. The pure SO_2 will be supplied in liquid form in high pressure cylinders. A heat exchanger using steam as the heat source may be needed to vaporize the liquid SO_2 to ensure proper gas flow. At the maximum SO_2 use of 600 ft^3/hr (99 lb/hr), 15,300 Btu/hr is needed which may be provided by approximately 20 lb/hr of saturated steam. Figure 7-4 is a schematic of the SO_2 supply and metering system.

7.4 Steam Supply

In the test facility, steam is used primarily for injection at the flare tip. Typically, saturated steam at about 100 psig is used. Steam is also needed for the ancilliary equipment such as the propane, N_2, CO_2 and SO_2 vaporizers.

Maximum steam requirement for the 12 inch flare test is approximately 200 lb/hr at 100 psig. The fuel system requires approximately 1500 lb/hr of saturated steam.

7.5 Input Flow Controls and Metering

The flare test involve many inputs, such as fuel, steam and air. These

TABLE 7-3. TRACER USAGE (FT^3/HR SO_2 AT 1% VOLUME IN FUEL)

Flare Size	Velocity, ft/sec							
	0.25	0.5	1.0	1.41	2.0	2.83	4.0	10.0
1½	0.11	-	-	0.62	-	-	-	4.42
3	-	0.88	-	-	3.53	-	-	17.67
6	-	-	7.07	-	-	20.0	-	70.7
12	-	-	-	-	56.6	-	113.1	282.1

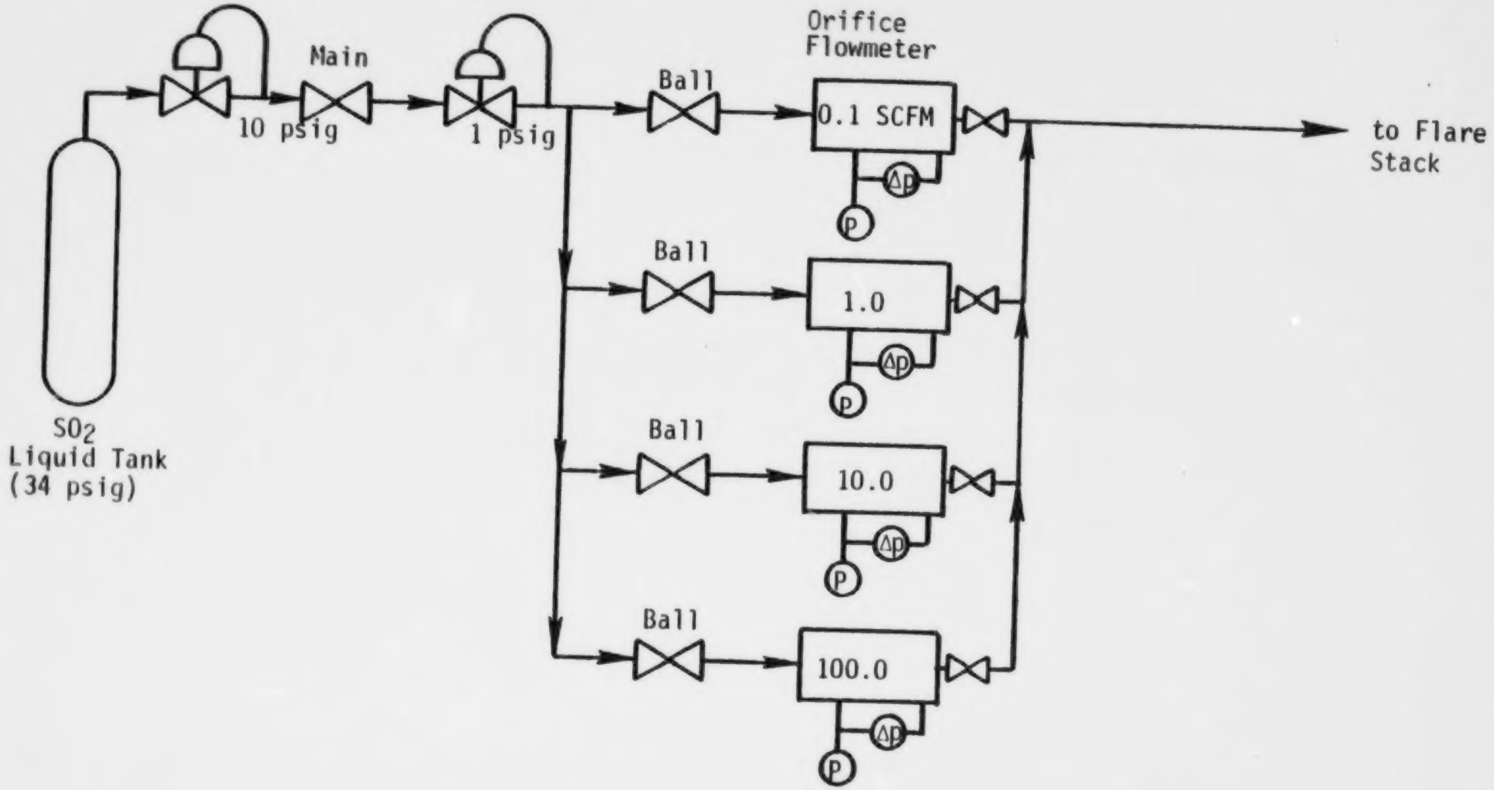

Orifice
Flowmeter
Main
10 psig
1 psig
Ball
Ball
Ball
Ball
0.1 SCFM
1.0
10.0
100.0
Δp
P
to Flare
Stack
SO_2
Liquid Tank
(34 psig)

Figure 7-4. Flare - tracer supply and metering.

flow rates vary over a wide range and each have to be controlled accurately in order to insure the quality of the data. Table 7-4 lists the design ranges of flow rates for the input streams. Typically, the flow control systems have to be accurate over a 2600:1 operation range. Since most flow meters can only operate with satisfactory resolution and accuracy for a maximum turn-down of 10:1, multiple flow meters sized for different capacities will be used to measure the flow rates.

7.5.1 Fuel Metering

Four orifice flowmeters calibrated against laminar flowmeters will be used for each of the propane, methane and N_2/CO_2 streams. With a typical usable turndown of 10 and accuracy of ±1 percent, the four flowmeters should cover the full operating range. Figure 7-5 is the flow schematic of the fuel gases. Controls for the different gases are conceptually similar but are sized for their respective flow rates.

The differential pressure from the flow meters will be measured with inclined manometers inside the control room. The operator can adjust the various flow rates by the control valves from the control room and need not be exposed to the intense radiation present during high flaring rates. The metered gases will be blended in a manifold to form a homogeneous mixture which is then delivered to the flare stack.

To reduce fire hazard, the propane and methane systems can be purged with either nitrogen or carbon dioxide. This is necessary during start-ups, shutdowns, and periodic maintenance of the flow controls and meters. The fuel system valves will shut off fuel flow on power failure or loss of the pilot flame. Flame arrestors will be installed downstream of the flow controls to prevent flame flash back into the system.

7.5.2 Tracer Metering

The tracer SO_2 gas constitutes about 1 percent of the fuel stream and it has to be metered over a range of 2600:1 at ±1 percent accuracy similar to the fuel gases. Four rotameters sized to cover the flow rates will be used to measure the flow rate. Figure 7-4 has illustrated the metering and control for the SO_2 flow. The arrangement is identical to those of the fuel metering systems.

TABLE 7-4. INPUT FLOW RATES

Stream	1½" Flare @ 0.29 ft/sec. Minimum Flow (CFH)	12" Flare @ 10 ft/sec. Maximum Flow (CFH)
Total	11	28,200
Propane (56% vol.)	6.2	15,800
Methane (100% vol.)	11	28,200
CO_2 (92.7% vol.)	10.2	26,100
N_2 (92.7% vol.)	10.2	26,100
Steam	0	2000 lb/hr

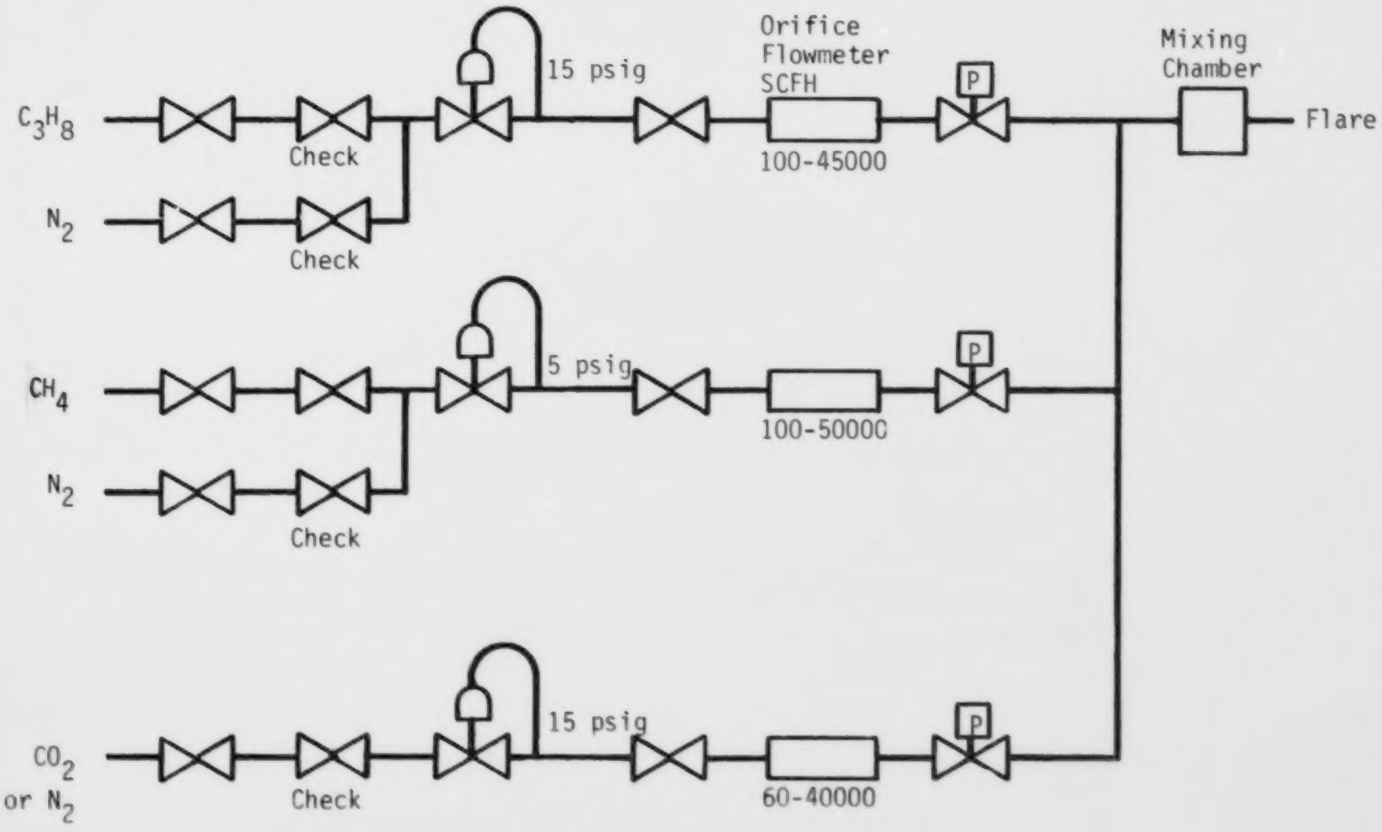

C_3H_8
N_2
CH_4
N_2
CO_2 or N_2
Check
Check
Check
Check
15 psig
5 psig
15 psig
Orifice Flowmeter SCFH
100-45000
100-5000C
60-40000
P
P
P
Mixing Chamber
Flare

Figure 7-5. Fuel control and metering system.

7.5.3 Steam Metering

The steam for injection at the flare head will be supplied by a self-regulating package boiler. Four orifice meters will be used to meter the steam flow rate as shown in Figure 7-6. The differential pressure signal will be registered with a pressure transducer which is isolated from the steam by gauge protectors. The steam flow is regulated with control valves by the operator in the control room.

7.6 Ambient Conditions Measurement and Control

The flare flame is exposed to the atmosphere and is subject to variations in ambient air conditions such as wind, temperature and humidity. The most important ambient factor is wind, because it affects the flame orientation, length, stability, and combustion characteristics. The effects of air temperature and humidity and combustion efficiency are not clear, but are believed to be insignificant.

For the flare tests, it is desirable to control the wind. Tests will be run under three conditions: quiescent, 7, and 14 mph. These conditions exist naturally, but are highly unpredicatable. In addition, the wind condition varies with the time of day. Therefore, to ensure progress of the scheduled tests, provisions have to be included to produce the desirable wind conditions consistently. Temperature and humidity effects are believed to be negligible and will not be controlled but will be recorded in the data log.

Quiescent conditions may be produced be erecting wind screens around the flare. This can be inplemented readily by installing perforated metal panels at strategic locations on the structure supporting the sample hood and the probes. The proposed site for the flare facility is located along a canyon and is protected from the wind on three sides. The prevailing wind follows the run of the canyon. Therefore, wind screens need to be erected on the windward face only. A rough estimate using a simple orifice model indicates that the wind forces may be attenuated by 90 percent if the open perforation area is about 6.5 percent of the total screen area. A pattern of round holes 5 inches in diameter on an 18-inch center triangular pitch will be adequate to attenuate the wind.

Flares under the influence of a crosswind may be tested with the wind

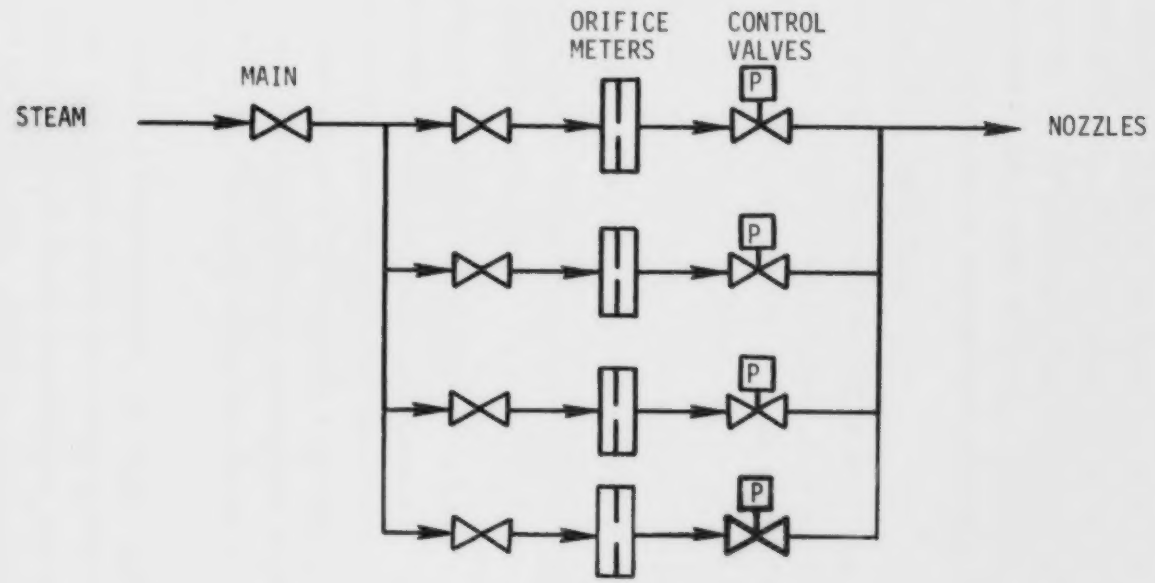

STEAM
MAIN
ORIFICE METERS
CONTROL VALVES
P
P
P
P
NOZZLES

Figure 7-6. Steam metering.

screens removed when the natural wind conditions meet the test requirements. However, it is unlikely that the natural wind conditions will remain constant throughout an experiment. Therefore a wind generator is preferred. It will consist of a windbox and four fans with a combined power of 100 hp. The wind generator will produce winds with a maximum speed of 14 mph covering an area 8 feet wide and 30 feet high. The wind speed will be controlled by throttle dampers on the intake side of the fans. Figure 7-7 shows a schematic of the optional wind generator with the support structure for the hood and probes. During all tests, the wind velocity and direction will be measured with a three-cup anemometer and a wind direction indicator. Air temperature and humidity will be determined by thermometers with dry and wet bulbs.

7.7 Measurement Techniques

The major goals of the program are to determine the global efficiency of pilot scale flares and to develop methods to apply this information to large industrial flares. The measurement program that is required to achieve these goals may be divided into three major areas:

- Determination of global flare combustion efficiency.
- Characterization of flame structures.
- Determination of the contribution of the flame structures to overall combustion efficiency.

To determine the global combustion efficiency of flares, the mass flux of pollutants exiting the flare should be determined. This can be done in two ways: by determining the instantaneous mass flux of pollutants, $\rho u c_i$, and averaging this value over a sufficiently long time and a large enough plane to encompass all significant pollutants leaving the flame; or by capturing all the effluents from the flame and measuring the mass flux of pollutants through the capture device.

Ideally, velocity, concentration, and temperature should be measured simultaneously over the entire flame for a long period of time. In practice this is impossible, and less rigid measurements can be made without compromising the quality of the data. Velocity, concentration, and temperature should still be measured simultaneously but need not be measured in every position nor at different positions simultaneously. Measurements of this type

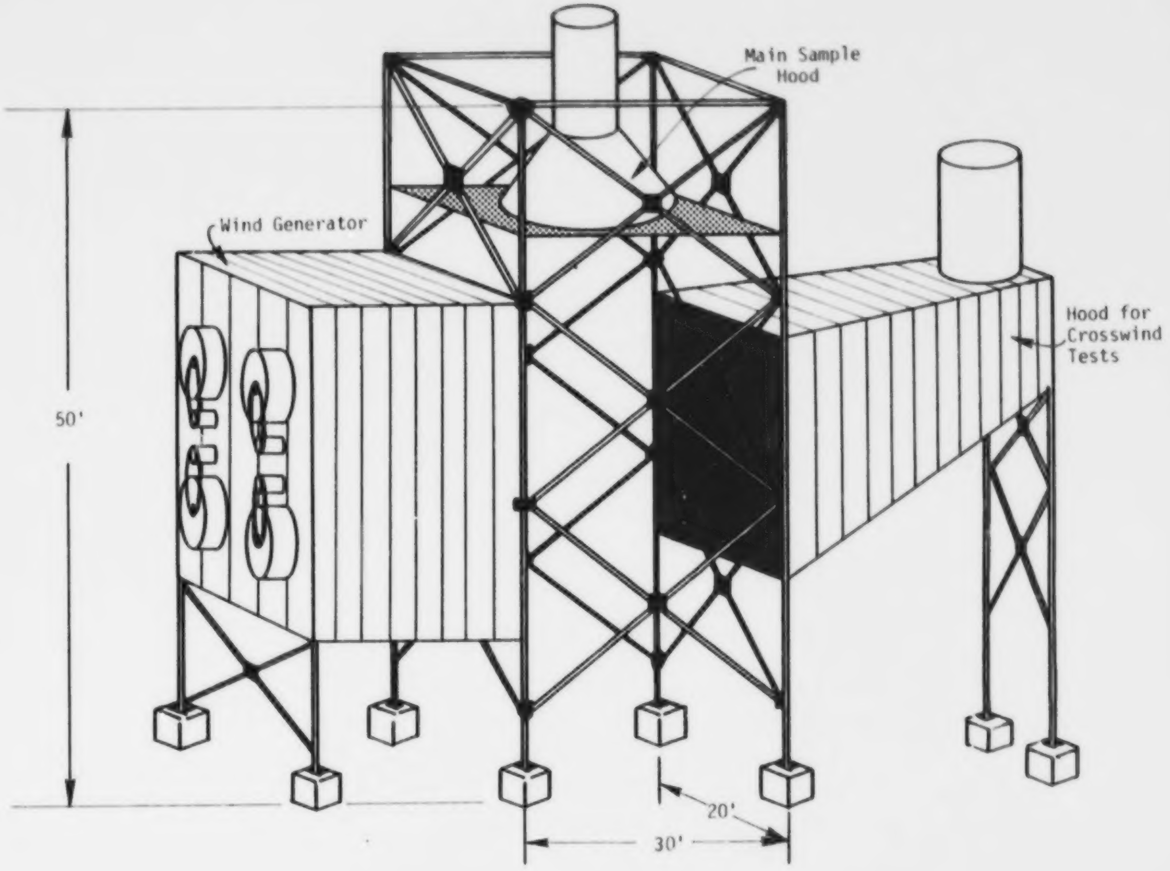

Main Sample Hood
Wind Generator
Hood for Crosswind Tests
50'
20'
30'

Figure 7-7. Wind generator, support structures, and sample hoods.

will yield accurate results provided there is a long time average which represents the mass flux at each point. In addition, measurements can be restricted to a single plane above the flare for the purposes of calculating emissions. In a hood sampling system, the effluents are collected and confined in a stack of known geometry. This confinement makes measurements of velocity, concentration and temperature easy compared to measuring these quantities in the flare flame.

A tracer which has a diffusive velocity similar to the combustion products (for instance, SO_2) should be added to the fuel. Use of a tracer reduces the uncertainty of caluclating the dilution factor and allows local efficiencies to be estimated directly.

The characteristics of the flame structures of the pilot scale flares can be defined by in-flame measurements of velocities and temperatures and by photography. Contribution of flame structures to overall combustion efficiency can be determined by in-flame measurement of mass fluxes. Three photographic techniques will be used to record flame structures. A TV camera should be used to continuously record average flame length and flame shape and slow fluctuations, and a high speed motion picture camera should be used to record the frequency of eddies shedding, the size of eddies, and the life of eddies. Still photography will record long time-averaged flame properties. Results from these techniques can then be used as empirical inputs to models of flare flames.

7.7.1 Global (Overall) Combustion Efficiency

The global (overall) flare efficiency can be determined by measuring the instantaneous values of density, velocity and concentration of pollutants, and integrating these in time and space. It can also be determined by capturing the entire effluent and measuring the gas concentrations. Siegel (1980) employed the first technique and was unable to account for all the inlet carbon. He suggested that the discrepancy was caused by the inaccuracy of the velocity measurements. Other reported work (Howes, et al, Lee, et al, Palmer) did not attempt to determine global efficiency by mass balance measurements.

In this program, both measurement methods will be used in conjunction with a gaseous tracer (SO_2). Emphasis will be on extractive sampling while optical techniques will be tried if the equipment and expertise are available.

7.7.1.1 Global Efficiency by Integrating Mass Fluxes

This method is based on the following relationship:

mass flow rate of carbon in species i: $$\frac{W \int_0^T \int_0^A \rho \, Ci \, U \, dA \, dt}{\int_0^T dT}$$

where W is the weight of carbon per mole of species i, lb/mole

ρ is the local molar density, $\frac{\text{mole}}{\text{ft}^3}$

Ci is the local mole fraction of species i, $\frac{\text{mole}}{\text{mole}}$

U is the local axial velocity, $\frac{\text{ft}}{\text{sec}}$

A is area, ft^2

T is time, sec

The global efficiency can then be caluclated by comparing the total carbon in the combustion product CO_2 in the effluent with the carbon in the inlet fuel. This method will produce confident results only if a near perfect carbon balance is achieved. This requires the measurements of all carbon-containing species, some of which are difficult to measure precisely.

7.7.1.2 Global Efficiency by Sampling with Collection Hood

The overall efficiency of a small flare flame can be more simply and accurately measured by capturing all the effluents from the flame in a hood. The concentration, velocity and temperature measurement techniques are identical. The difference is that the hood will collect all effluent products and mix them into a homogeneous mixture. The global efficiency can be determined by single time-average gas concentration measurements. The concept of a hood is shown in Figure 7-8. It avoids the time, expense and inaccuracies of trying to measure instantaneous point velocities, densities, and concentrations, and then integrating these over all regions where material might escape the flame. Successful application of a hood depends on two criteria:

- All flare combustion products must enter the hood.
- Presence of the hood does not affect the flare process.

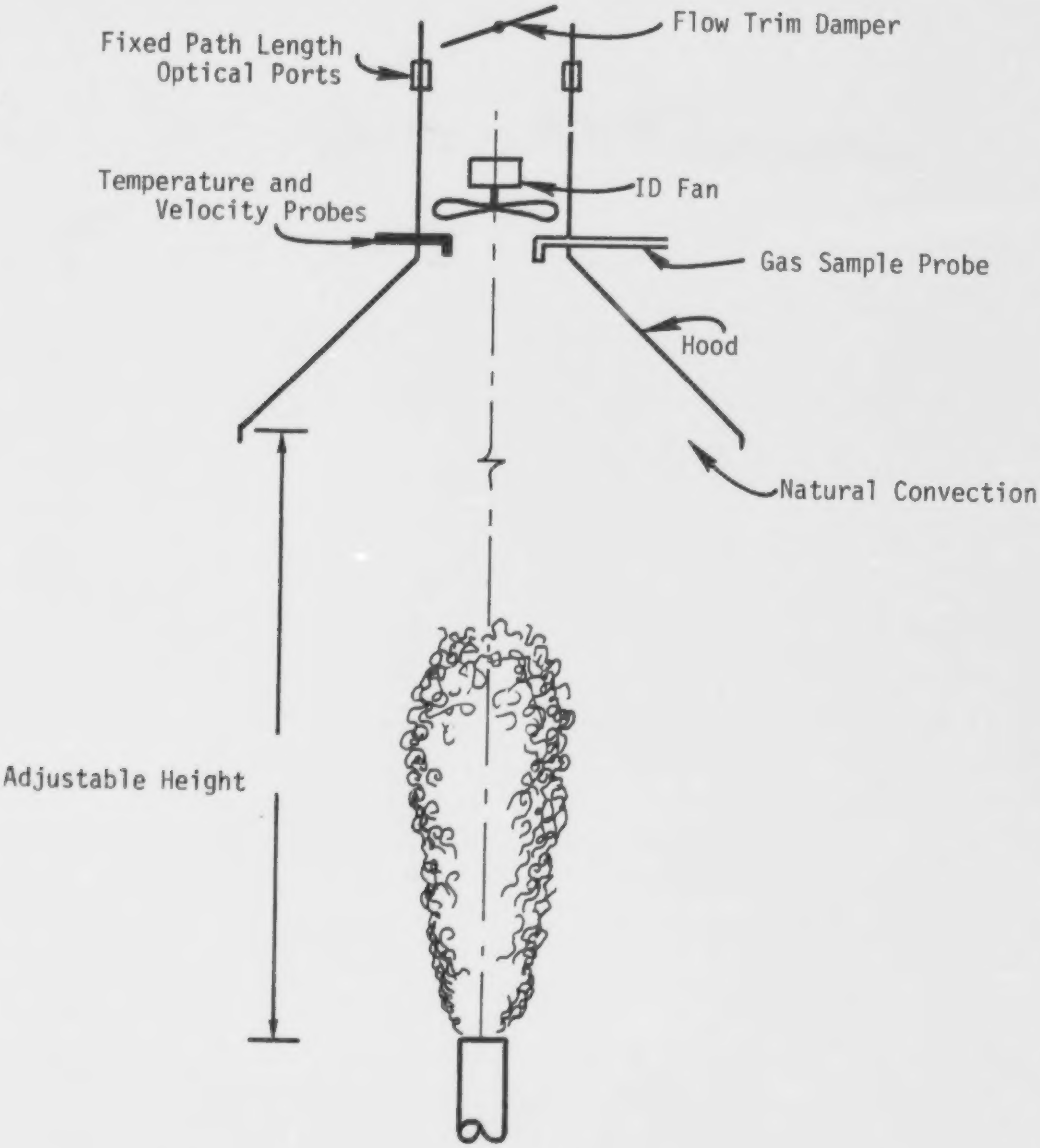

Fixed Path Length Optical Ports
Flow Trim Damper
Temperature and Velocity Probes
ID Fan
Gas Sample Probe
Hood
Natural Convection
Adjustable Height

Figure 7-8. Exhaust gas collection hood for pilot scale flare.

The first criteria may be met by designing the hood based on conservative principles as outlined in the Air Pollution Engineering Manual (Danielson, 1973) for hot sources, assuming that the heat is released from a long cylindrical flame. A fan may be used to aid collection of the combustion products if it can be demonstrated that it does not affect the flare flame.

To ensure that the hood does not affect the flare, the test flare should be operated in still air without the hood while the visual characteristics of the flame are recorded. Subsequently, the hood should be mounted so that its height is adjustable. As the hood is lowered, any changes in flame characteristics should be noted. The hood will be at the optimum point when it is close enough to capture all combustion products without visually altering the flame. This procedure should be aided by long exposure photography. The combustion products might be diluted excessively before they enter the hood and could render the species measurements difficult; therefore, some compromise in hood position may be necessary.

Hood design for a flare is complicated by the wavering flame. At any off-axis location above the flame, an imaginary probe will "see" the flame a fraction of the time, approximately as shown on Figure 7-9 for a non-reacting turbulent jet in still air. For example, at a radial distance to axial distance ratio of 0.16, the flame will be present 60% of the time. The hood should cover a divergent cone of 14 degrees half angle, corresponding to a radius to axial distance ratio of 0.24. Figure 7-10a shows the two outlines for a flare flame and the approximate averaged steamlines without the hood. The air flow pattern with the hood present is shown in Figure 7-10b and is almost unchanged. Thus, the location of the hood vertically close to the flame may only minimally distort the flame combustion process. The additional dilution by air flow, needed to insure that all products enter the hood may have a small effect and should be verified.

7.7.2 Application of Tracer Gas

Use of a tracer will reduce some of the problems in measuring emissions from flares. The tracer allows local efficiencies to be directly calculated from measurements of composition and can aid in estimating the overall efficiency of the flare flames. In previous studies by Palmer (1972) and Lee &

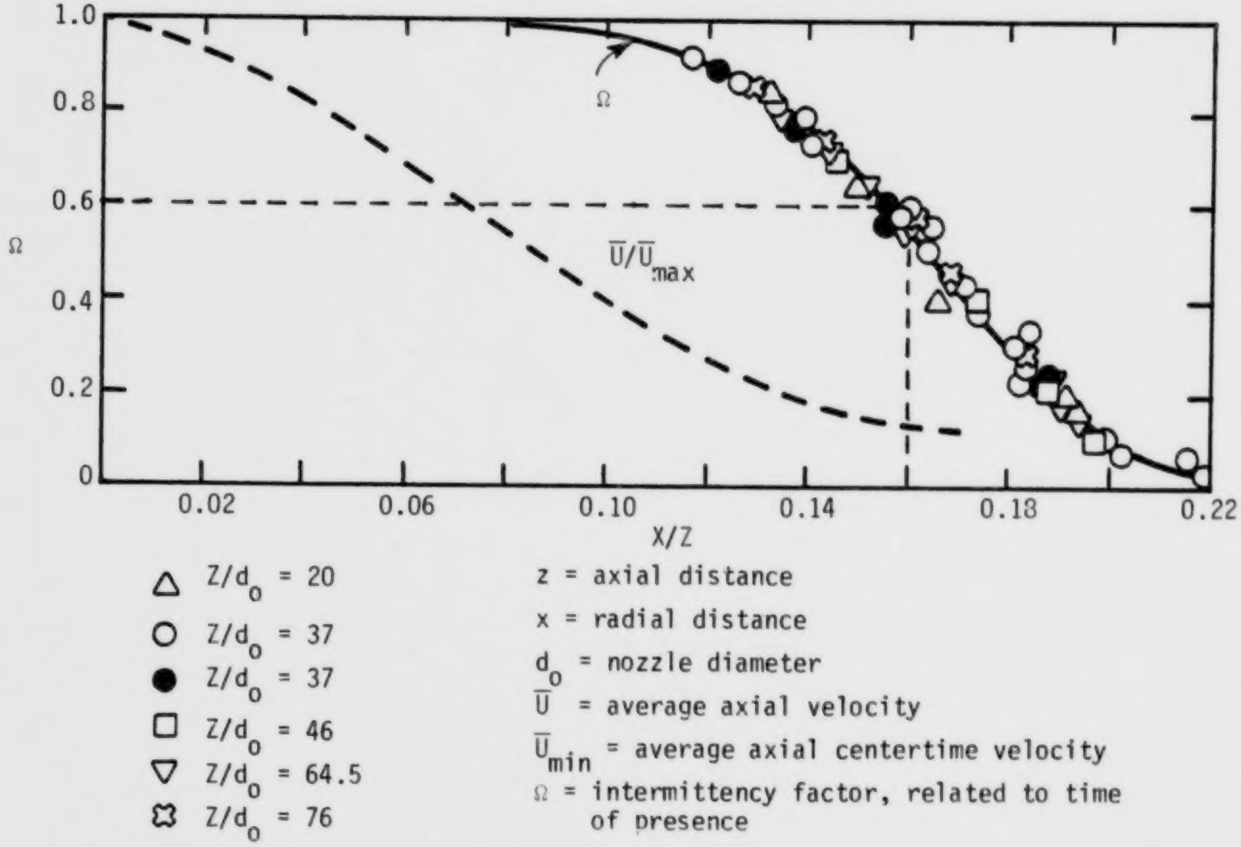


Figure 7-9. Distribution of intermittency factor, Ω, and mean forward velocity in a round free jet (Corrsin & Kistler, 1954).

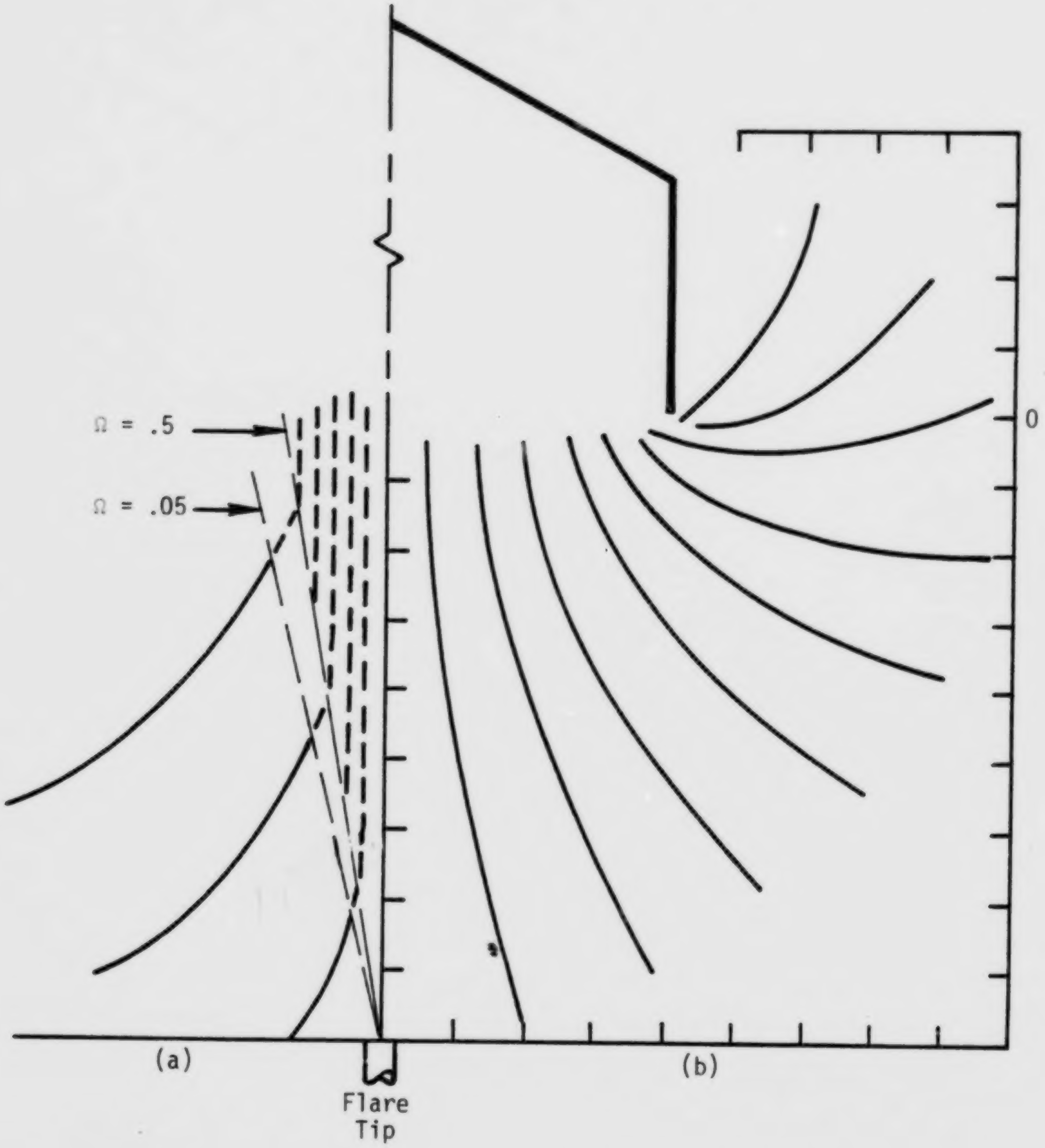


Figure 7-10. (a) Approximate streamlines in a turbulent round jet. The spreading angle is shown for two values of intermittency factor, Ω.

(b) Airflow streamline drawn into a hood, from Air Pollution Engineering Manual, 1973.

Whipple (1981), helium at various concentrations was used as the tracer to calculate local destruction efficiencies by formulas such as:

$$DE = \left[1 - \frac{[C_3H_8] \times DF_{\text{measured}}}{[C_3H_8]_{\text{inlet}}} \right] \times 100$$

where

DE = local fuel destruction efficiency

DF = dilution factor

The dilution factor is the ratio of concentration of helium in the fuel to that at the location of interest in the flare.

Helium is inert and exists at very low concentrations in ambient air. However, it has a diffusivity five times that of carbon dioxide and propane and when used as a tracer may produce distorted dilution factors. With a molecular weight of 2, helium is almost 15 times lighter than air and will most certainly change the buoyant properties of the flame if it is present at high concentration. Palmer's study (1972) suggested that the minimum detectable level of helium by a mass spectrographic technique was 10 ppm, which may also be regarded as the best resolution, In order to produce meaningful helium concentrations for dilution calculations Lee & Whipple used 10 percent helium in a propane flame. But at this level the diffusivity and density differences between helium and the host compounds probably affected the flame process. This concern is further confirmed when the measured dilution in Lee's experiment was higher than the prediction by Ricou and Spalding's mass entrainment model (1961). Also, at the high helium addition rates, the cost of helium makes it less attractive when other gases, such as SO_2, may perform well as a tracer.

A better tracer for flare studies than helium should be selected. The tracer gas used in the flare studies must meet these criteria:

- Diffusivity and density similar to host compounds.
- Inert and conserved through the flare.
- Detectable at low concentrations with adequate accuracy.

- Low background level.
- Low cost.

Though not an ideal tracer, SO_2 has many advantages:

- Its diffusivity and density approximate the host substances closely.
- SO_2 can be detected at very low levels. Resolution of 1 ppm may be possible with carefully designed instrumentation.
- SO_2 is readily available at reasonable costs.

One concern for using SO_2 is that potentially some SO_2 may be converted to other sulfur compounds in the flame. The concentration of other sulfur compounds should be measured and if significant SO_2 is converted, then total sulfur should be used as the tracer instead of SO_2.

7.7.3 Extractive Sampling

The most critical experimental task is the accurate determination of the concentrations of O_2, CO, CO_2, SO_2, hydrocarbons and soot. The concentrations of these species at the sample hood and above the flame will indicate the global and local combustion efficiencies, respectively.

7.7.3.1 Concentration Measurement Considerations

The difficulties of sampling and measuring the gas concentrations in the flare tests are:

- The withdrawn material may not statistically represent an intermittent flame.
- The concentration of solids can be different from the concentration in the flame if the sampling is anisokinetic. However, this problem should be minor, since the particles will be small.
- The concentration of gases and solids can be altered if the sample is inadequately quenched.
- The low species concentrations.
- The high sample dew point.
- The presence of particulates.

- The possible interaction between the gases and the material used in sample train.
- The large number of samples that have to be analyzed.

Errors in the measurements of flare efficiencies can arise from improper sampling. Improper sampling can produce major errors because of the fluctuating nature of a flare. The time required to obtain the concentration with a specified error can be estimated by statistical methods. Let θ be the classical jet spreading angle, then the area above the flame which eddies pass through is:

$$A_z = \pi z^2 \tan^2 \theta$$

where z is sample height above the flare. The cross-sectional area of an eddy is

$$A_e = \frac{\pi d_e^2}{4}$$

where d_e is the eddy size. On the average, the number of eddies that has to be formed before one eddy will pass by the probe is the ratio of the sampling area to the eddy area:

$$\frac{A_z}{A_e} = \frac{z^2 \tan^2 \theta}{d_e^2}$$

Now, the average time between eddies passing the probe is the number of eddies required for one to pass the probe divided by the frequency of eddy generation, f.

$$\tau = \frac{z^2 \tan^2 \theta}{d_e^2 f}$$

A sufficient number of eddies must be sampled in order to obtain statistically reliable species concentrations in eddies. The sampling duration is dependent on the behavior of the flame and has to be determined experimentally. It has to be sufficiently long so that the collected sample is representative of the time-averaged properties at the sample location.

The geometric size and shape of the probe is important in sampling because it can distort the flow field that is being measured. The distortion can be minimized provided the probe is small compared with the size of the flame eddies, and provided the probe has smooth aerodynamic shape.

Some error is mass loading and particle size distribution is inevitable when solid particles are sampled from a turbulent stream. A sample can be drawn at the average velocity of the stream; however, turbulent fluctuations in velocity and direction cannot be followed. Some distortion in the particulate sampled must be expected. This error should not be large for small soot particles. An example of the potential error in solid loading for sampling 5 and 10 μm particles from a gas stream flowing at 25 ft/sec and sampled at different velocities is shown in Figure 7-11. The error is less than 10 percent provided the ratio of gas velocity to sampling velocity is below a factor of 2.

The sample withdrawn from the flame will represent flame concentrations only to the extent that significant reactions cease to occur in the probe. Water-cooled probes capable of cooling the sample at up to 10^6 K/sec should be used to minimize this effect. However, even this rate is insufficient to quench many fast reactions. Furthermore, solids cannot be cooled as rapidly as gases, because they have large specific heats as compared to the low specific heats of gases.

Imperfect but acceptable probes have been designed to provide adequate quenching of withdrawn samples. The change in composition of the sample in the probe depends on the activation energy of the reaction, the rate of cooling and the rate of destruction of reactants. Table 7-5 shows that most reactions of interest for emission from flares can be quenched in less than a millisecond. This is less than the time of 3 milliseconds recommended by Chedaille and Braud (1972). However, during this time, species involved in reactions with low activation energies, such as oxidation of carbon monoxide, may be significantly altered.

Figure 7-12 shows a standard International Flame Research foundation probe suitable for sampling gases and solids from flames. The probe tip is aerodynamically tapered and is 22.5 mm in diameter. This is small compared to the expected size of the flame and eddies and is unlikely to disturb the flare flame.

Table 7-6 listed the estimated gas concentrations in and above the flame

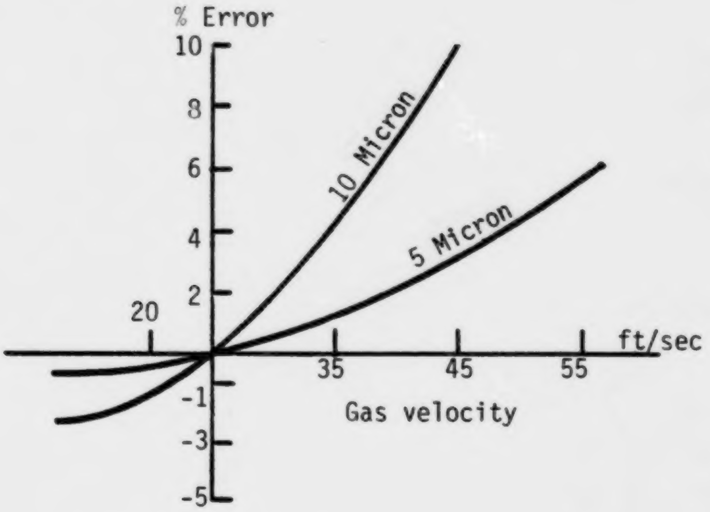


Figure 7-11. Errors in solid concentration for samples drawn anisokinetically (Badzioch, 1959, 1960; reprinted with the permission of The Institute of Energy).

TABLE 7-5. TIME TO QUENCH THE RATE OF REACTIONS TO 10% OF THE RATE AT 1500°K (CHEDAILLE & BRAUD, 1972; REPRINTED WITH THE PERMISSION OF EDWARD ARNOLD PUBLISHERS, LTD.).

Reaction	Activation Energies Kcal/gmole	Temp °K	Time Sec at 10^6 K/sec
Soot Oxidation	50	1320	1.8×10^{-4}
Hydrocarbon oxidation	3-6	486-699	1.0×10^{-3}-8.0×10^{-4}
CO Oxidation	1	191	1.3×10^{-3}

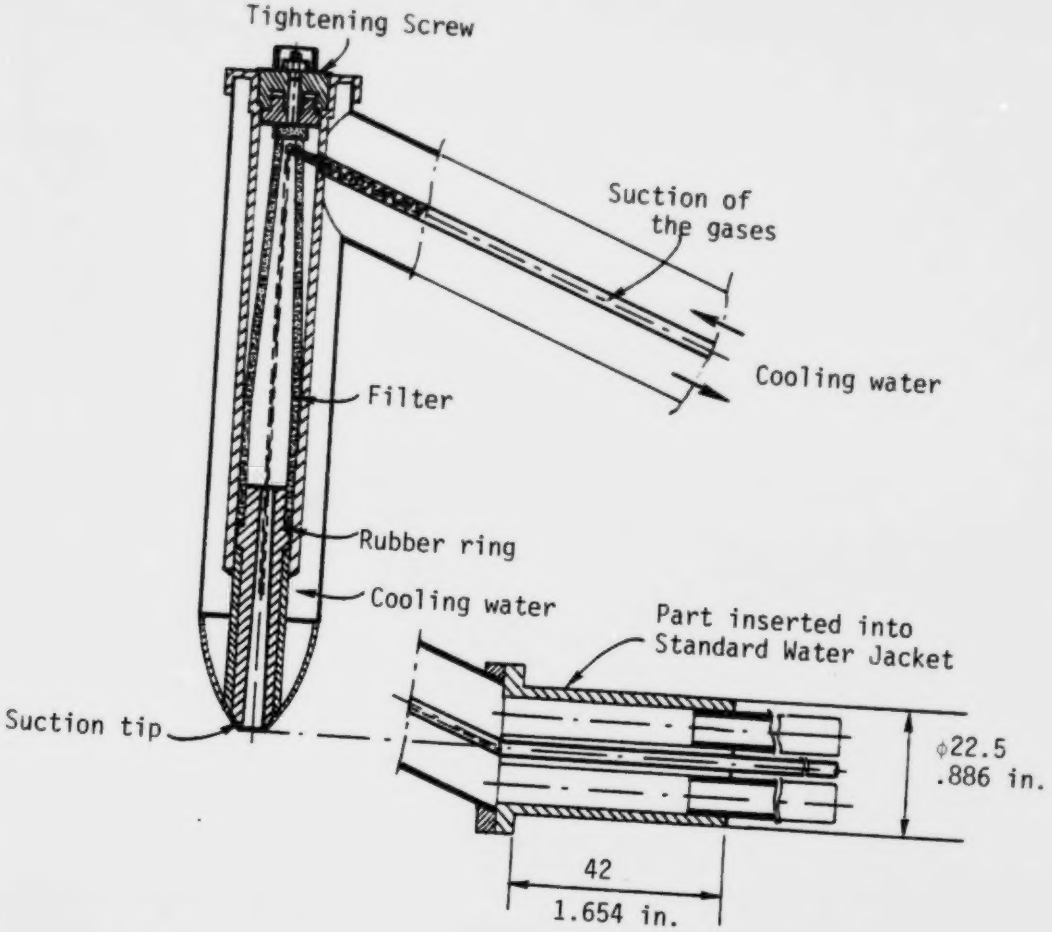

Tightening Screw
Suction of the gases
Cooling water
Filter
Rubber ring
Cooling water
Part inserted into Standard Water Jacket
Suction tip
ϕ22.5
.886 in.
42
1.654 in.

Figure 7-12. Water-cooled soot-sampling probe with exchangeable filters and filtertips (Chedaille and Braud, 1972; reprinted with the permission of Edward Arnold Publishers, Ltd.).

TABLE 7-6. SAMPLE GAS MEASUREMENTS

Continuous Gas Analyzers				
Gas	Analyzer Model	Full Scale Ranges	Expected Concentration	Precision
Oxygen	Beckman 755	1%-25%	19-21%	± .02% O_2
Carbon Monoxide	Beckman 315A	0-500 ppm	10-100 ppm	± 0.2 ppm CO
Carbon Dioxide	Beckman 315B	0-5%	0.2-2.0%	± 1% Full Scale
Sulfur Dioxide	Philips 8850	2.5-100 ppm	5-50 ppm	± .01 ppm SO_2
Hydrocarbons	Beckman 400	1 ppm-2% CH_4	10-100 ppm	± 1% Full Scale

Physical Property Measurements				
Property	Measurement Method	Range	Expected Value	Precision
Velocity	Turbine Meter	0.5-50 fps	0.5-20 fps	± 1%
Temperature	Thermocouple	0-1300°F	300-1000°F	± 1-10°F

and the recommended analyzers for each component. These analyzers were selected to cover the full range of the expected concentrations. Note that the analyzers are sufficiently sensitive for concentrations similar to typical ambient levels. They also encompass the concentrations near the flame which are similar to the levels encountered in source sampling.

The dew point of the flare combustion products is higher than the ambient temperature because water vapor is produced during hydrogen combustion and because steam will be injected during some tests to enhance fuel/air mixing. Some typical dew points for propane flare products are listed in Table 7-7. For example, on a day with 90 percent relative humidity and 70°F ambient temperature, the dew point at a dilution of 33 is about 137°F for a propane flame injected with 1 pound of steam per pound of propane. If the moisture were allowed to condense in the sample system, part of the gases, particularly SO_2, will be dissolved in the water and will introduce error in the sample analysis. Hence, the probes and sample lines will be kept above 160°F by hot water and electrical heat tracing in order to prevent condensation of water and loss of the SO_2 tracer in the lines. At a location close to the analyzers, the moisture in the sample will be removed by Perma-Pure dryers. These dryers selectively absorb water by a permeable membrane inpregnated with a hygroscopic agent. The absorbed water is continuously removed by dry air flowing on the other side of the membrane. Downstream of the dryers, the sample system need not be heated.

There is concern over whether the permeation dryers will change the SO_2 concentration in the gas sample. A study at EER (Case et al, 1982) showed that no evidence of SO_2 was found in the dry air side of the dryer. However, another study (Cassidy, 1974) showed that SO_2 losses of less than 4 percent of 50 ppm sample levels should be expected. Therefore, during the initial phase of the experiments, the effects of the dryers on SO_2 concentrations will be evaluated.

Soot particles will be produced from some flames and will be sucked into the sample probe. Accumulation of these particles along the sample lines will increase the surface area and contact time by which gases such as SO_2 and hydrocarbon are absorbed. This absorption may be reduced by minimizing the time and surface area of contact between the gas and the soot particles.

TABLE 7-7. DEW POINT (^{o}F) OF COMBUSTION PRODUCTS FOR PROPANE WITH STEAM INJECTION AT 1 LB STEAM/LB PROPANE

Dilution / Relative Humidity @ 70^{o}F	33	91	148
90%	137	110	99
50%	136	106	94

Therefore, filters will be built into the probes to remove these particulates. The design of the probes will be discussed in a later section.

The gas samples consist of reactive components such as hydrocarbon, CO and SO_2, which may be absorbed on some materials. Stainless steel and teflon have been shown to have the least affect on gas analyses among common construction materials. These will be the only materials allowed to come in contact with the gas samples.

Gas withdrawn from each probe must be analyzed separately. Continuous analysis of the gas from each probe would require a complete set of instruments for each probe.

Since only one set of analytical instruments will be available and species concentrations have to be determined at many locations for each flare operating condition, the sample system will operate in two modes, continuous and integrated. The continuous probe will be mounted at a selected location where the concentration fluctuarions need to be recorded. The time needed for each integrated sample depends on the fluctuations at the sample point and will be long if the intermittencies have long characteristic times. The actual sampling times will be determined experimentally. A probe rake with five separate collection trains will greatly reduce total sample time for the multiple sample locations. Use of the containers will also automatically integrate the fluctuations in the flame, provided the sample fill rate is kept constant.

7.7.3.2 Sampling Methods

In spite of the problems associated with using probes to withdraw samples from flares, our understanding of flames is based largely on samples withdrawn with probes. Provided precautions are taken to minimize these problems, errors in the withdrawn sample caused by probes should, in most cases, be small.

To adequately describe the emissions from a flare, measurements must be made at a large number of points on a plane sufficiently large so that no significant amounts of material escape undetected. The time and expense of operating the flare while sampling for sufficient time with a single probe would be prohibitive. Probes with multiple tips can reduce the cost of the experiment considerably as well as determine concentrations at different points simutaneously; therefore, multiple-tip probes should be used in flare studies. It should completely span the region of interest in one dimension and should be movable in the other horizontal and vertical directions.

7.7.3.3 Integrated Sample Collection

Figure 7-13 shows the grab sample system. Other researchers have used Tedlar bags to store gas samples. The advantage of the Tedlar bags is that they can be deflated easily, while rigid sample spheres have to be evacuated with vacuum pumps. A study conducted by Polasek and Bullin (1978) showed that samples of low concentration CO and "nonmethane hydrocarbons" were altered substantially over periods of several hours. Figure 7-14 illustrates their findings. Since alternatives such as stainless steel samples are expensive, this study will evaluate the Tedlar bags in the initial experiments and will select the proper sample container.

Gas samples will be drawn at a rate so that the retention time in the sample lines is less than 5 seconds. Depending on the desired sample integration times, the Tedlar bags will be filled at various flow rates. The contents of the selected bag is delivered to the analyzers by a sample pump. A rotameter will regulate the sample flow so that the analyzers can respond fully without depleting the gas sample.

7.7.3.4 Hood Sampling

The function of the hood is to physically collect the flare combustion products into a "well-mixed" zone where the different gases are homogenized. The combustion products will be sampled and analyzed and will provide a check for the global combustion efficiency determined from the multiple-point concentration, velocity, and temperature measurements.

The design parameters of the hood are its size and shape, height above the flare head, and the round chimney dimensions. These specifications depend strongly on the flame length, the jet spreading angle, and ambient air entrainment. The objective is to bring about the smallest hood that will capture all of the combustion products without adversly affecting the flame dynamics.

There are several formulations in the literature that predict flame lengths. However, they do not agree with one another, and for some cases, the

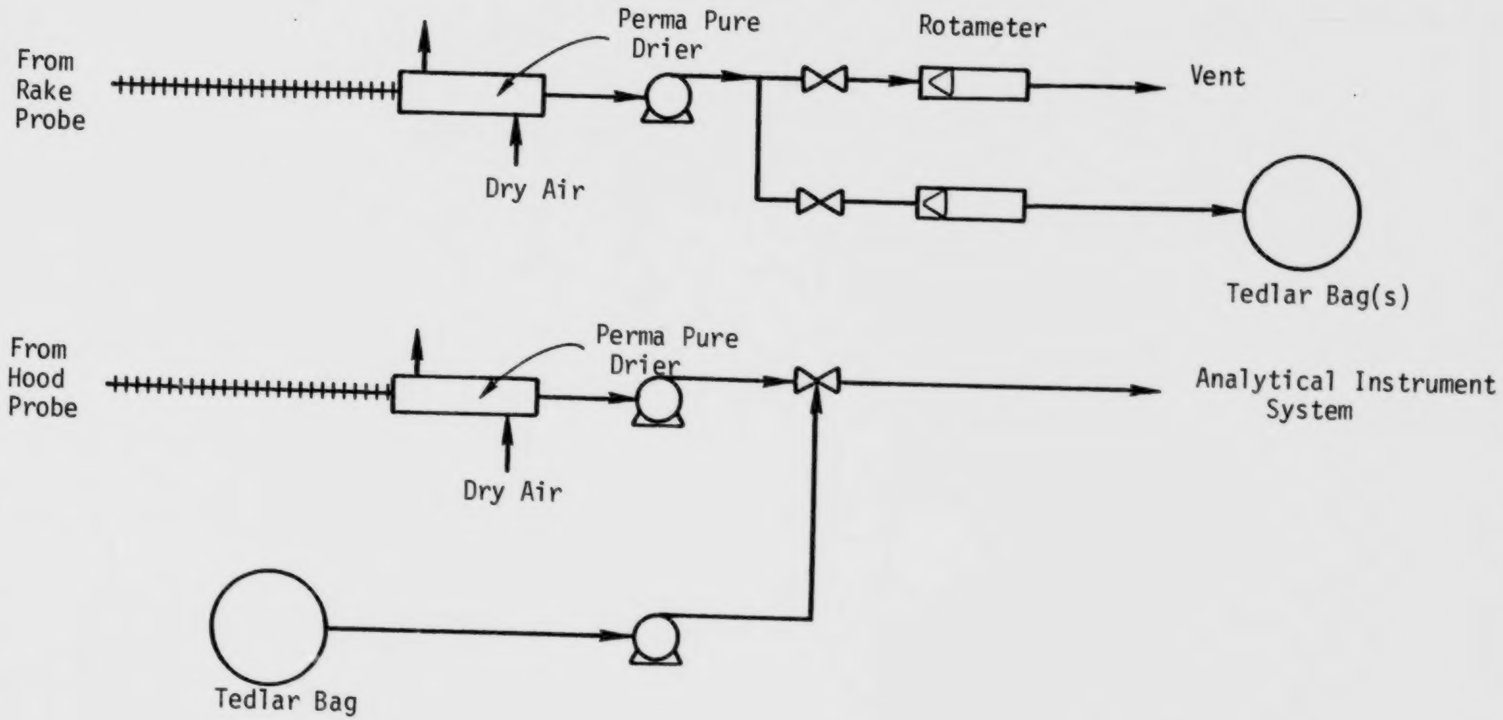

From
Rake
Probe
Perma Pure
Drier
Dry Air
Rotameter
Vent
Tedlar Bag(s)
From
Hood
Probe
Perma Pure
Drier
Dry Air
Analytical Instrument
System
Tedlar Bag

Figure 7-13. Sample system schematic.

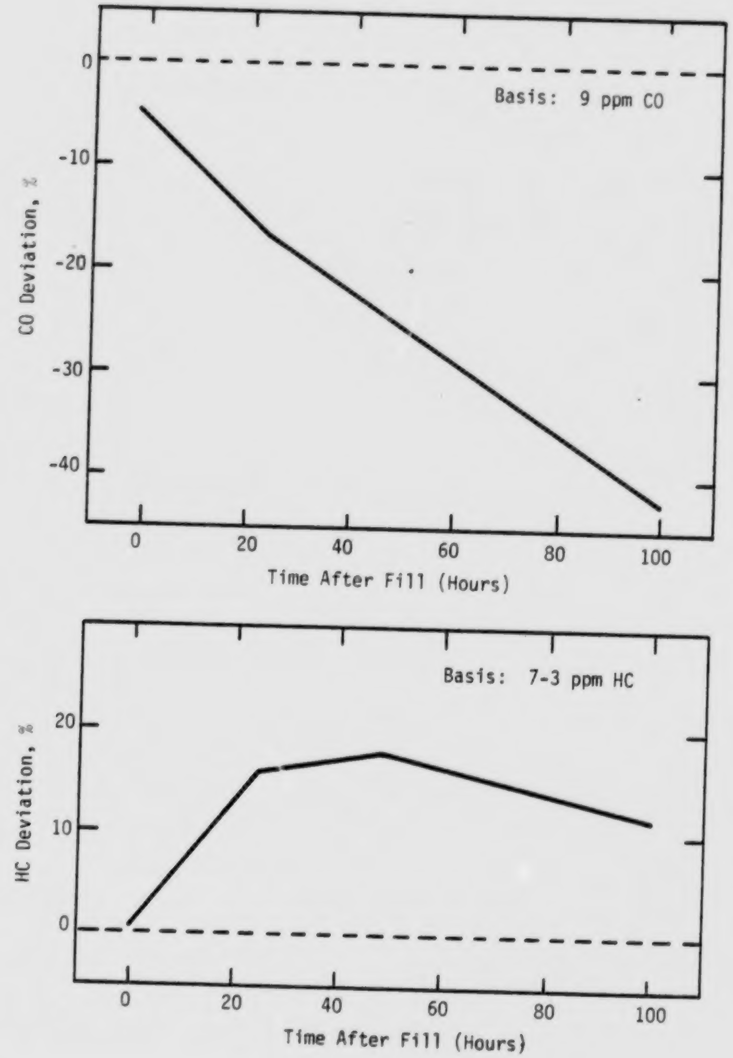


Figure 7-14. Tedlar bag sample concentrations changes with time (reprinted with permission from Polasek and Bullin, 1978; copyright 1978 American Chemical Society).

predicted lengths may vary by a factor of four or more. To date, the formulation by Brzustowski (1976) appears to predict flame lengths that are closest to real observations but tends to underestimate flame lengths. His model takes into account the molecular weights and densities of the fuel jet and the ambient air, jet and cross-wind velocities, jet nozzle diameter, and the flammability limit of the gas. The caluclation procedure for flame lengths is outlined in Appendix E. For the 3 inch flares, the nominal flame length is 20 feet. The flame length for the 6 inch flare can be 40 feet or more. A hood large and high enough to capture the combustion product of a 40 foot flame is too costly and is out of the scope of this program. Therefore, the hood has been designed for a 20 foot flame which diverges at a half-angle of 12°.

Concpetually, the hood, as shown in Figure 7-8, will have a nominal inlet diameter of 15 feet. The height of the 5 foot diameter chimney will be selected to generate natural draft so as to assist gas collection. A rough estimate of the pressure drop in the convergent section of the hood is 0.5 inches of water. This pressure drop will vary with the gas approach velocity at the hood inlet and is a function of the flare throughout, the amount of air entrained and the location of the hood. In order to minimize the effect of the hood on the flare flow dynamics, an ID fan will be used to restore the proper pressure and flow distribution above the flare. Assuming the gas approach velocity is 10 ft/sec across the hood entrance and the gas converges to a 5 foot diameter chimney, a 10 hp fan will be needed. A damper will be used to adjust the flow through the hood.

7.7.3.5 Sample Probes

Two types of material will be sampled: gas and solid particulates. As discussed earlier, the O_2, CO, CO_2, hydrocarbon, and SO_2 in the gas will be analyzed with electronic instruments. The solid particulates will be weighed to determine the solid loading in the sample. Both gaseous and solid samples will be extracted using the same probe.

The 5-probe support will be constructed of 3" x 3" box tubing. It encloses the five ¼" stainless steel tubes which carry the gas samples. Figure 7-15 illustrates the probe concept. Commercially available filters will re-

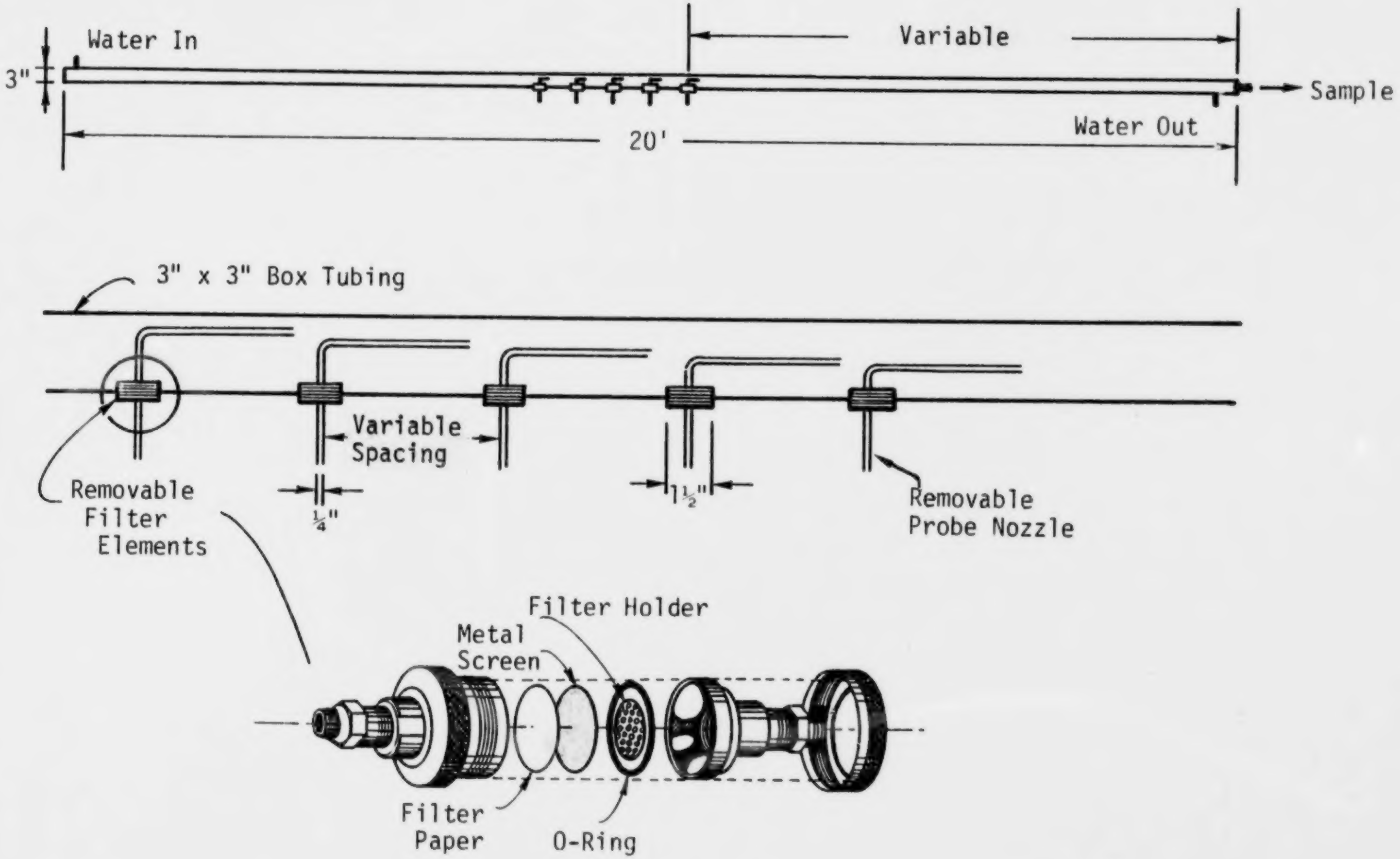

Water In
3"
Variable
Sample
Water Out
20'
3" x 3" Box Tubing
Variable Spacing
¼"
1½"
Removable Filter Elements
Removable Probe Nozzle
Filter Holder
Metal Screen
Filter Paper
O-Ring

Figure 7-15. Design of multi-rake probe.

move the solids from the gas. Half of the stainless steel filter housing is welded recessed into the box tubing. The other threaded half of the filter housing mates with the female thread of the welded half. The filter units can hold many types of filter, including cellulose membrane filters for low temperature application (350°F). Other filter media, such as glass microfiber, may be used for temperatures up to 930°F. Pore sizes down to 0.3 μm are available. Gas leakage is prevented by a Viton O-ring rated at 400°F. Hot water at 160°F flows inside the box tubing and cools the support and sample lines, and prevents condensation of the moisture in the sample lines. If high boiling hydrocarbons are present, compressed air will be used to control the probe temperature to minimize condensation of both the moisture and the hydrocarbons. Since the filter housing is recessed into the box tubing, it is effectively cooled as well. This will minimize the chemical reactions that may take place when hot reactive samples are drawn past the particulate-laden filter.

Different types of probe tips will be mounted to the bottom halves of the filter housings, depending on the temperature at the sample location. Outside the flame, where temperature is low, simple stainless steel tubes can be used. Inside the flame, water-cooled probe tips will be needed. Tips with bends can change the sample intake locations from the nominal spacings. Special intake nozzles may be used to capture the solid particulates nearly isokinetically. The soot particles are expected to be small (100-200 nm) and anisokinetic, and sampling will not affect the particle sample.

One probe with typical water-cooling channels will be located at the hood. A filter unit similar to those in the rake probe will capture the solid particulates. Typically this probe will draw samples that will be analyzed continuously.

7.7.3.6 Chemical and Particulate Analysis

The concentrations of O_2, CO, CO_2, hydrocarbons, and SO_2 will be analyzed with five instruments. The principles of operation of these instruments are:

- O_2 - Paramagnetic Properties of O_2
- CO - Non-dispersive Infrared Absorption
- CO_2- Non-dispersive Infrared Absorption

- Hydrocarbon - Flame Ionization of C-H compounds
- SO_2 - Wet Chemistry

A list of these instruments and their ranges and sensitivities has been shown in Table 7-7. Particulates will be measured by filtrations and weighing.

Oxygen

Oxygen concentration is an important indicator of mixing, combustion, and dilution. Oxygen concentrations between 9 and 20 percent have been measured in flares. Oxygen concentration could be measured with a paramagnetic analyzer with about 3 percent accuracy in the range of 0-20 percent. Interference from other gases is negligible.

Carbon Monoxide

Carbon can exit the flame partially burned, as carbon monoxide. Carbon monoxide concentrations of 0-5000 ppm have been measured in flare flames, and values of less than 10 ppm will significantly affect the flare efficiency.

Concentrations below 10 ppm of carbon monoxide can be easily measured with a nondispersive infrared detector. However, the sample must be dried to avoid interference from water vapor. Optical filters in the instrument will eliminate the interference by carbon dioxide.

Carbon Dioxide

The concentration of carbon dioxide at the exit of a flame provides verification of the efficiency of combustion. Concentrations of 0.5 to 7.0 percent of carbon dioxide should be accurate to better than one percent of the value of the composition for the measurements to be useful in determining flare efficiency. Table 7-2 indicates that the accuracy of measuring carbon dioxide is not high enough for direct calculation of flare efficiencies. However, it can provide a useful qualitative indication of flare efficiencies.

Carbon dioxide can be measured with a nondispersive infrared analyzer. Typically, no other compounds interfere with the analysis of carbon dioxide.

Gaseous Hydrocarbons

Unburned or partially burned fuel can escape the flame as gaseous hydrocarbons. Concentrations of hydrocarbons from 0 to 1200 ppm have been measured in flare flames. For the condition expected above the flare flame, concentrations less than 30 ppm of carbon as hydrocarbons can contribute significantly to flare inefficiency.

The concentration of hydrocarbons are best determined by a continuous technique so as to give local concentration fluctuations. Unfortunately, samples will disperse in the sampling line and reduce the time resolution.

Concentration of hydrocarbons can be very accurately and continuously determined by a flame ionization detector. This type of detector analyzes ions produced during combustion of hydrocarbons. The number of ions produced is approximately proportional to the number of carbon atoms but is different for different types of organic compounds.

Table 7-8 shows the relative response of the flame ionization detector to carbon atoms in various types of compounds. It is obvious that the response of the flame ionization detector is not directly proportional to the carbon content of the mixture; however, differences are small for the types of unburned compounds expected to exit a flare flame.

Sulfur Dioxide

Sulfur dioxide is used as a tracer to improve the reliability of the data. A compound such as SO_2 is relatively inert and diffuses at a rate similar to the fuel and combustion products and can, therefore, be used to determine the extent of dilution of the gas sampled. Sulfur dioxide has not previously been used as a tracer; however, injection of SO_2 in a concentration of a tenth to one percent of the fuel would result in exit concentration of 1 to 10 ppm.

Accurate measurement of SO_2 requires special sampling precautions. Sulfur dioxide can be lost by absorption on particulate or sampling surfaces, by absorption into water and by condensation on surfaces. To minimize these effects, particulate matter would be removed and the sample should be maintained above the dew point.

Few simple and quick ways to analyze SO_2 exist. Ultraviolet absorption, pulse fluorescence, and flame photometric detection are some of the developed means of measuring SO_2. A flame photometric total sulfur analyzer will measure the sulfur. It has a wide sensitivity, ranging from parts per billion levels to a maximum of 10 ppm. The high sensitivity allows the tracer SO_2

TABLE 7-8. RESPONSE OF FID TO CARBON ATOMS IN COMPOUNDS (BECKMAN, 1970)

Molecular Structure	Relative Response Factor
Aliphatic Compound	+1.0
Aromatic Compound	+1.0
Olefinic Compound	+0.95
Acetylenic Compound	+1.30
Carbonyl Radical	0.0
Nitrile Radical	+0.3

flow to be minimized and reduces the possibility of physical and chemical influences by the SO_2.

Particulates and Soot

Soot can contribute significantly to the inefficiency of flares. Soot concentrations of 0.1 to 80 mg/m^3 have been measured in flares (Howes, et al, 1980, and Siegel, 1980). The effect of soot concentration of efficiency was discussed in Section 2.4.3.2 which indicated that concentration of soot less than 10 mg/m^3 must be measured to within about 1 mg/m^3 to accurately determine the efficiency of flares.

The concentration of soot will be determined by weighing the soot captured on a filter in the probe tip from a measured quantity of gas. This method of determining soot concentration has time resolution equal to the sampling time.

7.7.3.7 Remote Optical Techniques

Use of optical techniques can eliminate the mechanical problems, time and expense associated with probing a flame. However, such techniques are sophisticated and still require that the mass flux, in the case of absorption along a line of site, be measured by probing or by LDV. The following sections discuss three attempts to optically determine the efficiency of flares, namely the Remote Optical Sensing of Emissions (ROSE) System, and two using the Differential Absorption Laser (DIAL).

To date the ROSE system has been the most successful of the optical techniques. The design and operation of the ROSE system has been discussed by Herget and Brasher (1980). The system can measure species concentration along a path in either absorption or emission. The system has been used to measure gas concentrations in flares and in plumes from utility stacks, brick kilns, jet engines and gypsum ponds (Herget and Brasher, 1980). Comparison of measurements made with the ROSE system and other techniques are rare. Herget and Brasher claimed that concentration measured in the plume of a jet engine by the ROSE system and from grab samples agreed "reasonably." Few other quantitative comparisons appear in the open literature.

Differential Infrared Spectrometry has been used less successfully to measure concentrations in flares. This technique was used in a study sponsored by the German Society of Petroleum Sciences and Chemistry to measure hydrocarbons in flares (Gurs, et al, 1981). The sensitivity of the techniques used in this study was inadequate to measure combustion efficiency of flares. However, reasonably accurate measurements of acetylene were reported.

A modification of this technique has been developed by Stanford Research Institute, the Differential Absorption Laser (DIAL). The technique has been used to measure SO_2, O_3, and NO_2 from power plant stacks and flares (Hawley, 1981). The technique was reported to measure concentrations to within 6 percent of that of a conventional monitor. The technique is not applicable to flares because it does not measure any species which contribute to flare inefficiency.

7.7.4 Velocity Measurement

In order to calculate local mass fluxes, the velocity distribution in the flare flow field has to be determined. Many unusual problems make measuring velocities in flares difficult. The instantaneous velocities at the sampling points are expected to be intermittent and to vary from velocities of less than 1 ft/sec to 20 ft/sec. Also, these velocities must be measured over a large plane and for a long time. The technique used to measure velocity ideally should have an accuracy better than 10 percent, a response time less than 0.2 second, and a resolution less than 1 inch. None of the standard techniques entirely meet the criteria for measuring velocities in flare flames. Five devices have been considered, namely, pitot, laser doppler velocimeter, balance pressure probe, turbine meter, and hot wire anemometer (see Table 7-9).

The pitot (Prandtl) tube has traditionally been used to measure velocity. It can only measure velocities accurately over a limited range (Table 7-10). The uncertainty in the velocity measured by the pitot probes becomes very large for velocities below 8 ft/sec because the velocity must be corrected for viscous effects, and this is extremely difficult. Also the pitot probe cannot measure velocities above 200 ft/sec accurately because of boundary layer separation.

In addition to the velocity range, the pitot probe has a number of other problems. The location, sharpness, and angle of the static pressure port all affect the accuracy of the measured velocity. The orientation of the probe

TABLE 7-9. COMPARISON OF TECHNIQUES TO MEASURE VELOCITY

Device	Range ft/sec	Errors	Response Time (sec)	Spatial Resolution (in)	Price $
Pitot	8-200	>25%	0.1	0.2	500-1000
LDV	?	unknown	depends on seeding	0.2	20,000
Turbine	0.3-150	±1%	0.15-2	2	500-1000
Hot Wire	0.1-100	unknown	<0.001	0.5	400
Combination Pitot & Hot Wire	0-17 17-100	unknown ± 3%	unknown	0.5	500-2500

TABLE 7-10. CONTROLLED PARAMETERS

PARAMETER	SENSOR METHOD	CONTROL METHOD	FLUCTUATION CHARACTERISTIC TIME, SEC	CONTROL MEASUREMENT FREQUENCY	DATA MEASUREMENT INTERVAL	COMMENTS
Propane Flow Rate	DPT	RV	60	C	5 Min	±1%
Acetylene Flow Rate	DPT	RV	60	C	5 Min	±1%
CO Flow Rate	DPT	RV	60	C	5 Min	±1%
CO_2 Flow Rate	DPT	RV	60	C	5 Min	±1%
N_2 Flow Rate	DPT	RV	60	C	5 Min	±1%
Propane Gas Temp	TC	Vaporizer	60	C	5 Min	±5°F Cntrl ±1°F Meas.
Acetylene Gas Temp	TC	Vaporizer	60	C	5 Min	±5°F " "
CO Gas Temp	TC	HXER	60	C	5 Min	±5°F " "
CO_2 Gas Temp	TC	Vaporizer	60	C	5 Min	±5°F " "
N_2 Gas Temp	TC	Vaporizer	60	C	5 Min	±5°F " "
Tracer Flow Rate	DPT	RV	60	C	5 Min	May be Slave of Fuel Flows ±1%
Tracer Temp	TC	Vaporizer	60	C	5 Min	±5°F Cntrl ±1°F Meas.
Flare Position	VPE	Motor	OI	OI	OI	±1 Inch
Hood Position	VPE	Motor	OI	OI	OI	±2 Inch
Probe Position	VPE	Motor	OI	OI	OI	±1 Inch
Generated Wind	Ane	Motor/Damper	OI	OI	OI	Wind Mach. Optional
Sample Flow Rate: Continuous	RM/DPT	RV	60	C	5 Min	±5%

C - Continuous
DPT - Differential Pressure Transducer
HXER - Heat Exchanger
OI - Operator Initiated
PT - Pressure Transducer

SP - Suction Pyrometer
TC - Thermocouple
VPE - Visual Photoelectric
Ane - Anemometer
RV - Regulating Valve

TABLE 7-10. CONTROLLED PARAMETERS (CONTINUED)

PARAMETER	SENSOR METHOD	CONTROL METHOD	FLUCTUATION CHARACTERISTIC TIME, SEC	CONTROL MEASUREMENT FREQUENCY	DATA MEASUREMENT INTERVAL	COMMENTS
Sample Flow Rate: Rake 1-5	RM/DPT	RV	60	C	5 min	±5%
Sample Sphere Pressure	PT	Vac Pump	1	C	1 sec	±1%
Sample Sphere Fill Rate	RM/DPT	RV	1	C	1 sec	±1%
Sample Flow Rate (Instrument)	RM/DPT	RV	1	C	1 sec	±2%
Permapure Dryer Air Flow Rates	RM/DPT	RV	60	C	5 min	±5 F
Heated Line Gas Temp	TC	E. Heater	60	C	5 min	±5 F
Sample Spheres Temp	TC	E. Heater	60	C	5 min	±5%

also affects the accuracy, and alignment of the probe with the intermittent flow present in flare flames is impossible. Turbulent fluctuations also affect the accuracy of the velocity. Finally, pitot probes are subject to plugging.

Overall, the pitot probe has a velocity range of 8-200 ft/sec, an uncertainty greater than 25 percent, a response time of 0.1 sec, a spatial resolution of a fraction of an inch, and a cost of $500-$1000. The inability of the pitot to measure low flow rates and the high uncertainty make the pitot probe inappropriate for a study of flares.

The laser doppler velocimeter (LDV) could theoretically be used to measure velocities of gases exiting from flare flames (Durst, et al, 1976). LDV can measure velocity in the appropriate range with small but poorly identified errors. LDV records fast, but has undetermined time response. Spatial resolution is good, but LDV is expensive.

The major disadvantage of using LDV to measure velocities in flare flames is the complixity and the care required to accurately measure velocities in large flames. The velocimeter would have to be moved to measure the velocity at each point for a statistically significant time. Light would have to be back-scattered from and into a long probe to avoid problems of beam alignment and flame refraction.

LDV has other potential but poorly-defined errors. Natural seeding (i.e., natural presence of optically active particles) would have to be relied on in the large flare flames. This seed level could be maldistributed and result in biased measured velocity. Insufficient seeding will yield unreliable statistics during the fluctuations of interest.

Therefore, although LDV has the potential for measuring velocities in flare flames, it should not be used as the primary technique to measure velocities, because it is complex, geometrically difficult to use in large flames, has undefined errors, and is expensive.

Hot-wire anemometry has been successfully used to measure velocities in many cold isothermal, clean flows. The velocity range, response time, spatial resolution, and cost are all satisfactory for applying this device to measuring velocities in flames. However, the errors associated with use of hot wire to measure velocities in intermittently fluctuating flames are unknown, and apparently could be very large. In addition, maintaining the integrity, cleanliness, and stability of the probe in a large turbulent flame is impossible. Consequently, hot-wire probes are not recommended for use in future studies of flares.

Small turbine flow meters have typically been used to measure wind velocities in the atmosphere and appear to be applicable to measuring exit velocities from a flare flame. The error, spatial resolution, and price of turbine air flow meters are all satisfactory for use in flares. However, the range of velocity that can be measured and the response time of the turbines are marginal.

Velocities exiting the flare flame may be as low as a fraction of a foot per second. Such low velocities are difficult to measure with turbine probes because of the inertia of the rotating blades. Commercially available turbine probes are limited to measuring velocities above 0.3 ft/sec. However, this may cause an insignificant error, since the integrated mass flux is the quantity of interest. If the average velocity was 10 ft/sec, the neglecting of the flux of material which leaves the flames at velocities too low to measure would probably result in an error of less than 5 percent.

The spatial resolution of commercially available turbine meters is marginal for studying small flares. Turbines as small as two inches are the typical lower size limit. This size turbine will be satisfactory for the larger eddies, which are expected to be several inches. An average velocity will be measured for eddies smaller than two inches since the speed of a propeller is typically proportional to the velocity. Spatial resolution is then reasonably satisfactory.

A unique air flowmeter using a combination sensor that is based on flow induced differential pressure is also commercially available. This type of probe was used by Siegel (1980) in this flare study. The probe is constructed with two openings at the probe tip. These openings are connected together by an internal stainless steel tube. Purge gas is injected into the tubing in an arrangement which forms a pneumatic bridge. At zero line velocity, the bridge is balanced so that no flow occurs through the sensing portion of the tube, and purge exhausts equally from both openings at the probe tip. As flow occurs across the tip, a differential pressure proportional to the velocity squared is developed, unbalancing the bridge and causing a very small amount of purge gas to flow through the sensing section. Purge gas still exhausts out both openings preventing the main line gas from entering the probe. This prevents fouling. Thermo-electric sensors measure the shift in temperature gradients along the heated portion of the tube. This is related to the main gas flow creating the differential pressure at the tip. The accuracy of this device is unknown at velocities below 17 ft/sec. Applicability of this probe in a hot and fluctuating environment is unknown.

The turbine meter is selected as the primary device because it is rugged, has acceptable spatial resolution, and is capable of measuring an acceptable range of velocities. The turbine meter selected for this project has a three-inch diameter head and responds linearly over the range of 1 to 30 feet per second. It may be used in temperatures up to 480°F provided the bearings are purged continuously. The response time of the turbine meter is 30 msec, and is marginal for tracking the transient fluctuations. It may be feasible to complement the turbine meter with a temperature compensated hot wire anenometer to track the fluctuations qualitatively. Since velocity measurement techniques are not fully developed for fluctuating non-isothermal flow, the methods will be assessed in the early phase of the experiments.

7.7.5 Temperature Measurements

Measurements of temperature are required to calculate the density of the gas leaving the flame and to aid in developing scaling principles, models, and interpretation of data. Temperatures have long been measured in flames, and accurate and rapid techniques are available.

The response time of bare thermocouples depends on their size, but can be less than one millisecond. Response times need to be only as fast as those for other instruments which, for the study of flares, could be as long as 100 milliseconds.

Radiation losses from the thermocouple cause the greatest error in measured flame temperatures. These can be corrected by calculations, electrical compensation, or by reduction of radiation loss. The most common method for large flames is to use a suction pyrometer, which increases the convective heat transfer to the thermocouple and reduces the radiation loss from the thermocouple. Use of the suction pyrometer increases the time response of the system. The time response of a large suction pyrometer may be as long as one minute. Small pyrometers have been constructed which have response time on the order of seconds, possibly still too slow for a study of flares. These techniques have been well-developed and studied by the IFRF (Chedaille and Braud, 1972) and these techniques should be considered for studies of flares.

Thermocouple should be coated to avoid catalytic reaction on the thermocouple. The coating also makes the emissivity estimates easier for radiation calculations in clean systems. However, the emissivity of the thermocouple changes in sooting systems and hence the correction for radiation losses is difficult to make.

In regions where the temperatures are below 1300°F, unshielded thermocouples coated with high-temperature cement can be used. The coating is necessary to prevent measurement error caused by catalytic reactions that may occur on the metal surface. The estimated error caused by radiation of the unshielded thermocouple is less than 1 percent for temperatures under 1300°F. For higher temperatures, suction pyrometers will have to be used because the error caused by radiation heat loss increases sharply. Unshielded thermocouples are standard instruments and are readily available. The suction pyrometer will be about 10 feet long and will be fabricated in house, patterned after a design by the International Flame Research Foundation.

7.7.6 Characterization of Flame Structures

The structure of flare flames should be determined to aid the understanding of the mechanism of the emissions from flares and to guide development of scaling principles and models. The structure of a flare flame continuously changes in time and space and has been discussed in Section 2.5. The flame has been shown in photographs and schematically represented in Figures 2-7, 2-22, and 2-23. The emissions from flare flames are affected by generation of low-momentum, buoyancy-driven eddies in the shear layer of the flame. Consequently, measuring the shape and size of the flame and the eddy size, shape, production frequency, and life are necessary for understanding the performance of flares.

Photographic techniques can yield great insight into the turbulent nature of flare flames. The photographic techniques to be used should have sufficient time resolution to capture the formation and life of individual eddies and high enough spatial resolution to identify small eddies which may contribute to emissions. It should produce film that is easy to interpret, lead to quantitative information on flare flame structure and be inexpensive and convenient.

Photographic techniques have led to better understanding of many flames, for instance, Wohl, et al (1949), Brötz, et al (1980). Emission photography allows a straightforward interpretation of flame structure. Other techniques rely on optical interference to show density gradients, and the photographs are difficult to interpret.

For the flare tests, still photography and high-speed cinematography will capture the flame structures on film for close inspection and analysis. A video camera and a recorder will routinely monitor and record the flare flames on magnetic tapes.

7.7.6.1 Still Photographs

Still photographs will primarily record the overall flare characteristics such as flame length, orientation, and radiation intensity. Black and white photography will catalog the flame behavior of each test condition. Color photographs will supplement the monochromatic high-speed movies by providing information on color of the flames.

Since the camera will be mounted at strategic locations away from the control room, the camera must have an automatic film winder and a remote-activated shutter. A single-lens-reflex, 35 mm camera with the above accessories is inexpensive and will meet the test requirements. Two principle types of film will be used. The monochromatic Kodak Panatomic-X film (ASA 32) has extremely fine grain. A 35 mm negative of a 10 foot flame can resolve details that are 0.025-inch in size. The color film will be Kodak 2483, designed for photomicrography.

7.7.6.2 High Speed Movies

The reason for shooting high-speed movies is to record the formation and life of individual flare eddies on film. It is estimated that speeds around 500 to 1000 frames per second will be sufficiently fast to track the moving eddies. Various combinations of lens filters and film will allow study of sections of spectral emissions from the flame.

Two high speed 16 mm movie cameras were considered, namely, the Hycam and the Milliken cameras. They operate under different principles. The film in the Hycam camera is advanced continuously and is synchronized with a prism that acts as the shutter control. During exposure, the film moves along with the light image. In the Milliken precision high-speed camera, the film advances frame by frame and is controlled by a register pin. The shutter opens when the film is held still. As a result of the film advance mechanisms, the Hycam camera can shoot at 11,000 frames per second while the Milliken camera can only reach 500 frames per second. However, the Milliken camera can produce sharper images because the film is stationary while being exposed. Both cameras should be adequate for this research program and may be rented from local vendors. Therefore, during the early experiments, the two cameras will be evaluated so as to select the proper camera for subsequent experiments.

At the high frame rates, large amounts of film will be used. Typically, the Hycam can hold 400 feet of film. It takes 0.75 seconds to speed up to 1000 frames per second, and will expose the reel of film in about 16 seconds. The beginning 300 or so frames will have uncertain lapse times between frames.

Many types of 16 mm film are manufactured by Kodak. In this project, the film must have fine-grain size in order to resolve the eddies in the flame. However, films with small-grain size typically require longer exposure times. Therefore, the selection of film will be a compromise between time and spatial resolution. Three types of film will be tried in the early experiments, namely Kodak Plus-X (ASA64), Double-X, and 4-X. Other special films with high contrast and fine-grain size are available for the tests if the original film types are unsatisfactory.

In addition to the above film, infrared movie film is manufactured by Kodak in their specialty product line. The possible advantage of infrared movies is their ability to detect hot eddies that are not burning and are not emitting visible radiation. However, experience at the Jet Propulsion Laboratory (Dawson, 1981) has shown that infrared photography produced ill-defined images of flames that are difficult to interpret. Therefore, infrared movies will be produced only after infrared photography using the 35 mm still picture camera proves to be successful in providing useful information.

7.7.6.3 Video Recordings

The high cost and the high film consumption rate preclude the use of high speed movies for all experimental conditions. A video camera and a videotape recorder will be an inexpensive tool to monitor and evaluate the flare flame so that the high-speed movie camera may concentrate on the interesting regions of the flame. A color video camera and a standard videotape recorder made for home use will meet the requirements. In addition, the advantages of infrared detection techniques will be explored using video cameras that are sensitive to infrared radiation.

Also the video monitor will provide a continuous record of the flame location relative to the probe position. This will be useful in evaluating whether or not the probe is enveloped by the flame at any point in time. Either a fine grid on the probe support structure or a "lens grid" may be used to reference the probe location.

7.7.6.4 Image Analysis

Figure 7-16 illustrates the analysis steps for the various photographic records. The pictures from the still photograph camera and the high-speed movie camera will be viewed manually to reveal any interesting features. The formation and life of the eddies can be followed frame by frame to determine their sized, number density, frequencies of generation and shedding, lifetimes, etc. The monochromatic and color photographs will contain information on flame lengths, spread angle, orientation, radiation intensity and sooting behavior. It is anticipated that manual examination of the photographic images will be adequate to produce the required data.

If information in addition to that produced by manual viewing is needed, selected black and white frames can be processed with a scanning photo-densiometer which digitizes the images according to 256 levels of greyness. The minimum scanning area, called a pixel, is a 5-micron square which is the typical resolution limit of the Panatomix-X film. Typical processing time for a 16 mm frame using a 10 micron pixel is 10 minutes. Purchasing the scanning

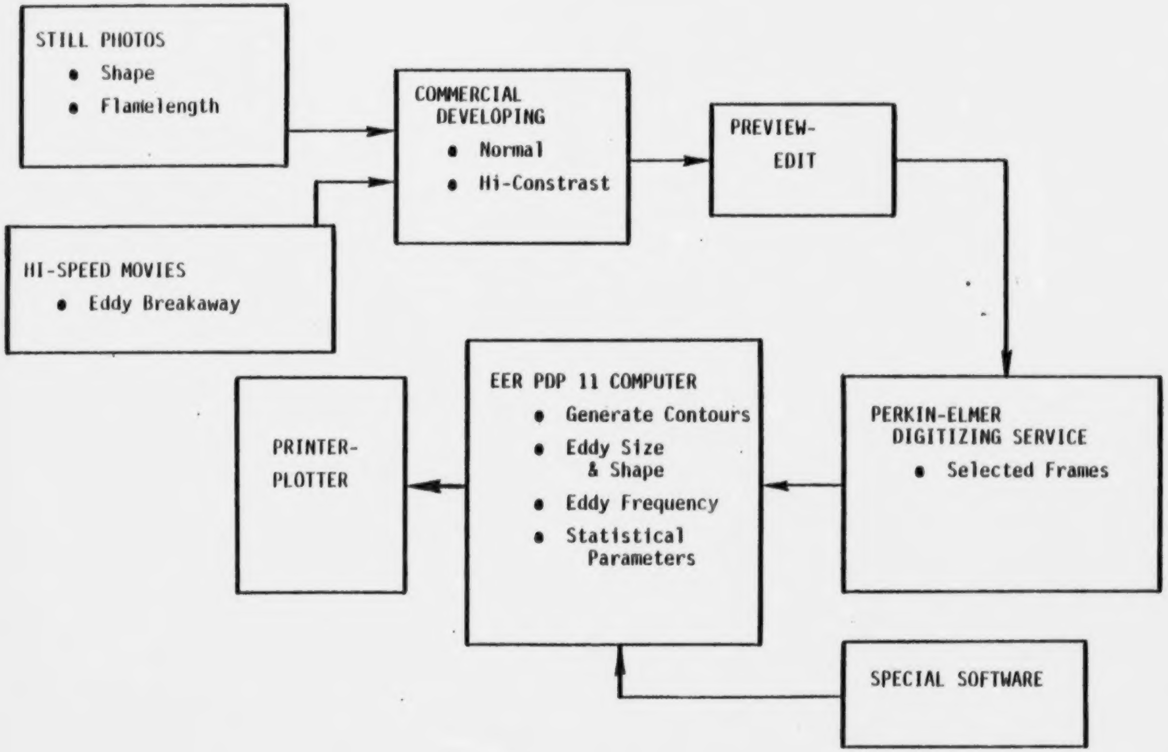

STILL PHOTOS
• Shape
• Flamelength
HI-SPEED MOVIES
• Eddy Breakaway
COMMERCIAL DEVELOPING
• Normal
• Hi-Constrast
PREVIEW-EDIT
PERKIN-ELMER DIGITIZING SERVICE
• Selected Frames
EER PDP 11 COMPUTER
• Generate Contours
• Eddy Size & Shape
• Eddy Frequency
• Statistical Parameters
SPECIAL SOFTWARE
PRINTER-PLOTTER

Figure 7-16. Photographic analysis.

photodensitometer is expensive ($100,000) and is not justified. Instead, Perkin-Elmer will be contracted to process the selected frames at a cost of about $75 an hour.

The output of the digitized image greyness may be recorded on magnetic tape. The PDP-11 computer at EER can examine the greyness data and compute flame lengths, generate equidensity zones, determine eddy sizes and their number concentrations. This analysis is expensive, but it is an objective method to evaluate the flare structures and will produce results more consistent than arbitrary assessment with the human eye. For obvious cost reasons, the extent of this type of analysis will be limited.

7.8 Control, Data Aquisition, and Processing

In order to conduct the flare test effectively, a system of controls, monitors, and data handling devices has been formulated. It takes into account the capital cost, development effort and the resultant savings in time, labor, and material costs.

There are two approaches to running the flare tests. One approach is to adjust system parameters and record data manually. The other is to use automatic control and data recording devices to provide the operator with sufficient real-time reduced data so that he can make sound decisions during the tests. Regardless of the approach, the test facility has to meet these requirements:

- Maintain operational parameters and conditions at desired set points.
- Minimize error in measurements.

The first criterion indicates the need for controls, which may be manual or automatic. The second criterion requires the use of accurate instruments and that the operator follows proper experimental procedures.

Table 7-10 lists all the independent system parameters that have to be controlled. In addition to these controlled parameters, Table 7-11 lists the system parameters and dependent variables that have to be monitored and/or recorded. As noted, some measurements are made on-line continuously while others are made intermittently. Some change rapidly, while others are fairly steady. Manual control and monitoring is adequate for slow responding parameters but

TABLE 7-11. DEPENDENT OUTPUT PARAMETERS

PARAMETER	SENSOR METHOD	CONTROL METHOD	FLUCTUATION CHARACTERISTIC TIME, SEC	CONTROL MEASUREMENT FREQUENCY	DATA MEASUREMENT FREQUENCY	COMMENTS
Sample Gas Concentrations	Analyzer	--	1 sec	---	C	O_2, CO, CO_2, HC, SO_2
Sample Point Gas Temp	TC/SP	--	.01 sec	---	C	Hood, Probe Rake
Sample Point Gas Velocity	Turbine Meter	--	.01 sec	---	C	Hood, Probe Rake
Particulate Loading	Weighing	--	60 sec	---	OI	1 per probe location

C - Continuous
DPT - Differential Pressure Transducer
HXER - Heat Exchanger
OI - Operator Initiated
PT - Pressure Transducer
SP - Suction Pyrometer
TC - Thermocouple

is ineffective for fast responding parameters.

The needs and specifications of the control data system may be defined by considering the tasks during a typical test which may include:

- Preparation and calibration of measurement system components such as probes, sample lines, sample conditioning devices, sample bags and analytical instruments.
- Prepare and adjust flare head hardware.
- Ignite flare and adjust fuel flow and compositions. Maintain conditions during test.
- Adjust steam and/or air injection rates. Maintain conditions during test.
- Position sample hood and adjust flow through hood.
- Continuously analyze gas samples from one probe.
- Position probe rake and collect grab samples.
- Remove particulate filters from probe and determine mass loading.
- Analyze grab samples collected in sample bags after test run.
- Position temperature and velocity probes and make measurements.
- Shoot photographs and movies of the flame.

After the test, the data have to be analyzed to produce maps of concentration, temperature, velocity, local combustion efficiency, dilution, and species flux. These local parameters have to be integrated over the flow field to give global combustion efficiencies.

After review of the test conditions and the requirements to record the data, it is concluded that although desirable, an automatic control and data recording system is too costly and is not justified. Instead, the data from various sensors, such as flowmeters, thermocouples, pressure transducers and gas analyzers will be manually recorded. The operator may adjust system conditions through the manual controls. A simple data logging chart recorder will aid the operation in temperature information.

8.0 APPLICATION AND ANALYSIS OF DATA

This section discusses the interpretation and analysis required to use the data gathered on the experimental flare flames. The interpretation of the data should:

- Establish the emissions of incompletely burned hydrocarbons and combustion products from individual pilot scale flames.
- Provide the basis for developing and verifying scaling principles and models of flare flames.
- Extrapolate, using the model, the emission factors established on experimental flare flames to estimate the emissions from commercial flare flames.

The prime objective of the study should be to establish the emission factors. However, the emission factors determined on small flare flames are meaningful only when extrapolated to commercial scale flames. This will require a thorough understanding of the mechanisms of pollutant formation, and the formulation of a model of flare flames if reliable extrapolation is to be achieved.

8.1 Independent Variables

The experimental data generated will consist of measurements of the effect of gas composition and heating value, flare tip size, tip velocity, wind speed, and rate of steam injection on flame structure, chemical and particulate concentrations, velocities, and temperature profiles of the flame. The range of operating conditions proposed for these variables is believed to be representative of commercial flaring practice. In addition, the values proposed for the independent variables have been selected so that scaling principles and models of flare performance can be formulated and verified. At least three scaling principles should be tested:

- constant tip velocity
- constant flame resident time
- constant Richardson number

In addition, scaling by a criteria related to eddy frequency (not yet developed) should be investigated. Since scaling principles are uncertain in combustion systems, the experimental results will be used to test existing scaling principles and to develop new ones.

8.2 Calculation of Emissions

Local efficiencies can be calculated using the concentrations of incompletely burned species and the tracer. A formula similar to

$$\eta = 1 - \frac{\left(\frac{12}{M_p}\sum_i n_i[HC_i]\text{ ppm} + 12\,[CO]\text{ ppm} + \frac{RT}{P\tilde{N}}M_i^{soot}\right)K_T}{[T]\text{ppm}\,M_T}$$

where

n_i = number of carbon atoms in HC_i

$[HC]$ = concentration of hydrocarbons

$\frac{RT}{P\tilde{N}}$ = conversion from volume to mass units

$K_T = \frac{\text{grams tracer in feed}}{\text{grams carbon in feed}}$

T = concentration of tracer in sample

M_T = molecular weight of tracer

M_p = molecular weight of product gas

Two properties of this equation are important: first, calculation of local efficiency does not require measurement of velocity or temperature; second, a local efficiency of this nature cannot be converted into a global efficiency without additional measurements.

Global efficiency of flares can be calculated by integrating instantaneous point values around the flare flame. Global efficiencies should be strictly calculated from

$$DE = 1 - \frac{\frac{12}{M_p}\sum_i \oiint\int_0^\infty \rho u n_i c_i\,dt\,dA}{\dot{m}_c}$$

where

c_i = concentration of unburned species

$\dot{m}_c$ = mass flux of carbon into the flame

the above equation can be simplified by integrating over a time sufficiently long, t, so that the value of the integral does not change, and by integrating the velocity (u) over a plane (dA) above the flame through which most of the unburned material passes,

$$DE = 1 - \frac{\frac{12}{M_p} \sum_i \int_{dA} \int_o^t \rho u n_i c_i \, dt dA}{\dot{m}_c}$$

The equation for the global efficiency requires that concentration of all incompletely burned carbon species, density, and velocity can be measured simultaneously over a plane above the flare for a time period t. Global efficiency can be approximated by use of a tracer. In this procedure the average mass is calculated to close a material balance on the tracer,

$$\overline{\rho u} = \frac{\dot{m}_T^{in}}{\frac{M_T}{M_p} \int_{dA} \int_o^t C_T \, dA dt}$$

This artificial mass flux can then be used to calculate the flare efficiency

$$DE = 1 - \frac{\overline{\rho u} \sum_i \frac{12}{M_p} \int_{dA} \int_o^t n_i c_i \, dt dA}{\dot{m}_c}$$

Use of this technique assumes:

- that no tracer escapes outside the plane of measurement
- that incomplete combustion products leave the flame by the same mechanism as the tracer.

The last assumption is questionable. If incomplete combustion products are the result of quenched eddies, then the tracer will exit the flare uniformly while incomplete combustion products will leave the flame as intermittent pockets of incompletely burned fuel. Consequently, such a simple notion, as an average mass flux, may be invalid.

Capture and measurement of the effluent from a flare is the most direct means of determining the overall emission. The material will be confined and homogenized in the hood. Consequently, it is likely that the concentration of incompletely burned material will only need to be determined at one point and that the sample need be integrated for only a short time, if at all. In addition velocity and temperature and hence mass flux are easy to determine in a hood. A simple measurement and calculation would yield the emissions from a flare from measurements in the flue of a hood:

$$DE = 1 - \rho u \frac{12}{M_p} \sum_i n_i c_i$$

A carbon mass balance should be used to verify the accuracy of any technique used to calculate the efficiency of flares. The mass balances should take the following forms:

for integration without using a tracer

$$\dot{M}_c in_t = \frac{12}{M_p} \sum_i \int_{dA} \int_0^t \rho u n_i c_i \, dt dA$$

for integration using a tracer

$$\dot{M}_c in_t = \overline{\rho u} \frac{12}{M_p} \sum_i \int_{dA} \int_0^t n_i c_i \, dt dA$$

and for the hood

$$\dot{M}_c in = \rho u \frac{12}{M_p} \sum_i n_i c_i$$

Measurement of the efficiency of flares is so difficult and has been so uncertain in the past that all the above techniques should be used to estimate the efficiency, compared and confirmed by use of a carbon balance.

8.3 Interpretation of Flame Structure

The structure of a flare should be interpreted from the TV picture taken to monitor the flare and the high speed motion picture film. The flame length, flame width, and flame angle can be determined from the TV screen as a function of flare size, velocity, gas composition, wind speed, and rate of steam injection. These results should supply empirical information for confirmation of previous empirical techniques, outlined in Section 2.3, used to estimate these properties or to develop new empirical techniques applicable over a wider range of flares sizes and conditions.

The high speed motion picture films should provide detailed information on the eddy structure of flare flames. The regions in which eddies separate, the frequency of eddy generation, the size of the eddies, and the behavior of eddies during their life should be derived by manually viewing, measuring and counting eddy behavior on the film. The results from the film will be used to formulate qualitative models of production of pollutants in flames. The data will also supply empirical input to models and verification for any models developed.

For instance, the structure derived from the film can empirically provide the frequency of eddy generation and the size and growth of eddies. This information could be used to modify the Broadwell model of turbulent flow. That is, the frequency of eddy generation specifies the rate of production of the stirred reactors in the Broadwell model, the size and life of the eddies specifies the time constants of the stirred reactors. Therefore, the experimental information supplies the distribution functions necessary to modify the Broadwell model of turbulent reacting flow to account for emission formation in eddies of flare flames.

The results from the studies of flame structure are much broader than a study of emissions from flares. The results should lead to a better understanding of the nature of mixing in flare flames in particular, but also in large turbulent diffusion flames in general. The results will be the first quantitative information on the formation and action of eddies in large flames. This information should be helpful to redefine our understanding of turbulent flow flames.

8.4 Scaling and Modeling

Measuring emissions on full scale, elevated industrial flares is beyond the present state-of-the-art and measurements made on small scale flares need to be scaled to commercial sized systems. Techniques to model and scale flares were reviewed in Section 2.5 but none of the existing models were found to be entirely satisfactory.

Scaling approaches were discussed in Section 2.5. Some of these may be partially applicable to scaling of flares. The important parameters in these approaches appear to be the residence time, and the Richardson number. The rate of heat loss will also be important. However, commercial flares discussed in Section 2.3 are designed based on constant velocity scaling. Therefore, both scaling principles are to be investigated. Unfortunately, no existing scaling technique has a parameter to account for the intermittent nature of flares. The generation, shedding, and life of eddies appears to be important in pollutant formation but is difficult to formulate, and the formulation of a parameter to account for eddy behavior should be part of any program on flares.

None of the available models reviewed in Section 2.5 are likely to be applicable to flares. A new model of turbulence being developed by workers at Caltech may be capable of predicting some aspects of flares but this model will not be finally developed in time for application at the commencement of this program. In addition, as in the available scaling approaches, the model only partially accounts for the statistical formation and behavior of eddies and hence will need to be supplemented with a model and experimental data on eddy generation to be fully applicable to flare flames.

8.5 Conclusions

A properly developed program on flare flames should result in the following benefits:

- Identify the magnitude of emissions of incompletely burned hydrocarbons and combustion products from commercial flares
- Provide information needed to estimate emissions from individual flares and the population of commercial flares
- Develop and prove new scaling and modeling techniques for large turbulent flare flames. Such models can be used to help identify and control emissions of pollutants for other large turbulent flames.

To ensure these benefits, emissions from flares should be calculated by a number of methods. However, many of the quantities required for these calculations are difficult to measure. Therefore, efficiency of flares should be calculated by all the methods outlined above, the results compared, and verified by a carbon mass balance. The results from viewing the flame structure should be used to verify old or newly developed methods of predicting flame shape and be used to develop scaling principles and models of flare flames. The existing scaling principles and models need to be modified to account for the intermittent nature of flare flames and this modification should be part of a program to determine the emissions from flares.

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APPENDIX A

Comparison of Commercial Flares (Brzustowski, 1976).[1]

Very little information is available on the design and operation of individual commercial flares. The information available is usually in manufacturers' brochures. However, Brzustowski reviewed and compared commercial flares in his 1976 review article. Brzustowski classified flare design into five types and listed the advantages and disadvantages. The types of design are shown in Figure A-1 - A-6 and described and analyzed in Table A-1 and A-2; flare manufacturers are listed in Table A-3.

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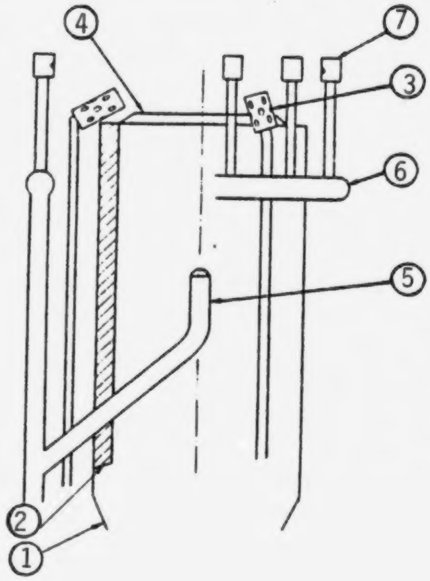
[1] This information is reprinted with permission from Progress in Energy and Combustion Science, 2, Brzustowski, T. A., "Flaring in the Energy Industry," Copyright 1976, Pergamon Press, Ltd.



1 - High-Temperature Alloy Tip
2 - Refractory Lining
3 - Pilot Light
4 - Nozzle Lip or Perforated "Flame-Holder"
5 - Center-Steam Nozzle
6 - Steam-Ring Header
7 - Steam-Ring Nozzle

Figure A-1. Principal elements of a "Steam-Ring" smokeless flare tip (Brzustowski, 1976; see footnote p. A-1).

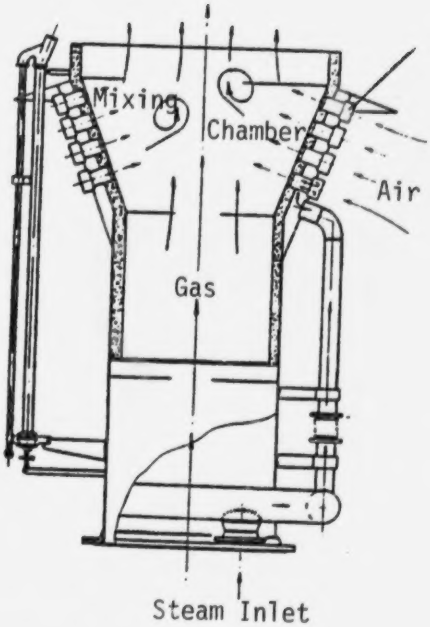
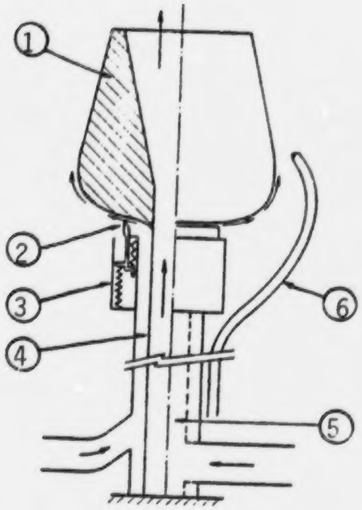
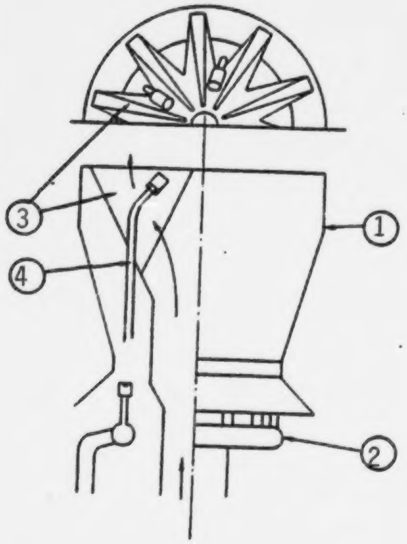

Mixing
Chamber
Air
Gas
Steam Inlet

Figure A-2. Principal elements of the flaregas FS antipollutant flare tip (Brzustowski, 1976; see footnote p. A-1).



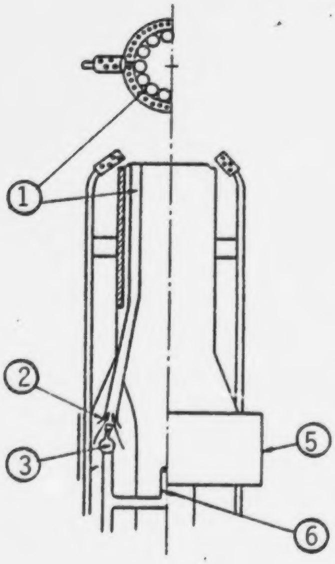
1 - Conical Nozzle Inside Contoured Burner Tip
2 - Adjustable Annular Nozzle for h.p. Gas
3 - h.p. Gas Nozzle Adjustment Mechanism
4 - Annular h.p. Gas Duct
5 - l.p. Gas Duct
6 - Pilot Light Assembly

Figure A-3. Principal elements of the Indair smokeless flare (Brzustowski, 1976; see footnote p. A-1).



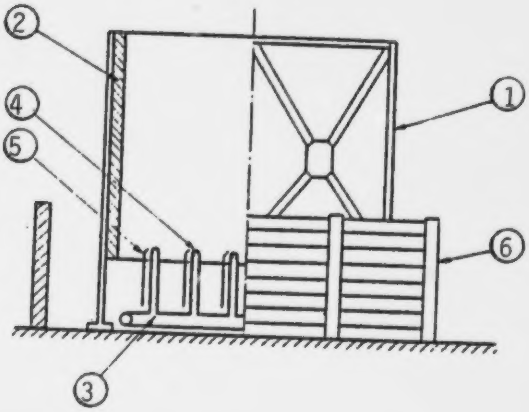
1 - Shroud
2 - Steam-Ring Header
3 - Hollow Spokes Carrying
Gas from the Central Duct
to the Radial Slit Nozzles
4 - Pilot Light

Figure A-4. Principal elements of the Smoke-Ban Model SVL flare tip (Brzustowski, 1976; see footnote p. A-1).



1 - Ejector Tubes Carrying Steam and Induced Air into the Flame
2 - Ejector Entrance Nozzle
3 - Steam-Ring Header and Nozzles
4 - Center-Steam Nozzle
5 - Acoustical Shroud

Figure A-5. Principal elements of the Zink Services SA field flare tip (Brzustowski, 1976; see footnote p. A-1).



1 - Exterior Frame
2 - Refractory Lining
3 - Flare Gas Header
4 - Flare Gas Burners
5 - Pilot Lights with an Independent Gas Supply
6 - Louvred Enclosured

Figure A-6. Principal elements of a typical ground flare (Brzustowski, 1976; see footnote p. A-1).

TABLE A-1. COMPARISON OF COMMERCIAL FLARE DESIGNS (BRZUSTOWSKI, 1976; SEE FOOTNOTE P. A-1)

Tips for Elevated Flares

Utility Flare Tips	
Construction	- tip as in Figure A-1 but without center steam nozzle (5), steam ring (6) or steam nozzles (7). - may have wind screens surrounding tip of flare
Advantages	- cheap, quiet, requires no utilities except for ignition system and gas for pilots - minimum of parts exposed to the flame
Disadvantages	- no provision for smoke suppression, can be used for flaring H_2, CH_4, H_2S, and CO but even small proportions of heavy or unsaturated hydrocarbons cause smoking
Availability	- from most suppliers e.g. - Flaregas series FN - National Airoil NCG - Samia standard flare - Zink series STF-U

Center Flare Tips	
Construction	- tip as in Figure A-1 but without steam ring (6) or steam nozzles (7) - may have wind screens surrounding tip of flare
Advantages	- cheapest provision for smoke suppression for installations in which only small quantities of heavy saturates and unsaturates are flared - hydrocarbons and steam are well mixed at low flaring rates even in a strong wind - steam nozzle not susceptible to flame damage in the absence of steam flow

Center Flare Tips, cont.	
Disadvantages	- steam is not used to entrain air into flame; as a result a greater proportion of steam to hydrocarbon is required for smoke suppression than in other smokeless flares - steam noise is possible at peak steam flows, depending on location and design of steam nozzle
Availability	- from several suppliers e.g. - Flaregas series FC - National Airoil NCS - Zink (not a designated model)

Steam Ring Flare Tips	
Construction	- tip as in Figure A-1; some designs do not include the center steam nozzle (5)
Advantages	- cheapest provision for smoke suppression for installations in which large flows of heavy saturates and unsaturates may be flared - steam is used to entrain air into the flame, lowering the proportion of steam to hydrocarbon for suppression of smoke - when fitted with a center steam nozzle can be used over wide range of flaring rates - this is the smokeless flare most widely used in refineries and petrochemical plants; proven designs available from several vendors
Disadvantages	- steam ring may be noisy (jet noise) at high smokeless flaring rates - steam ring alone is not very effective for low flaring rates, particularly in a strong wind, excessive steam use at these conditions may produce both jet noise and low-frequency noise (chugging) - steam ring and nozzles are susceptible to damage by flame in the absence of steam flow

Steam Ring Flare Tips, cont.	
Availability	- from several suppliers e.g. - National Airoil NRC - Samia Smokeless flare - Zink series STF-S

Proprietary and Special Purpose Flare Tips	
Flaregas Series FS Antipollutant Flare-Tip	
Construction	- tip as in Figure A-2; principal feature is a perforated conical mixing section into which air is entrained by steam-driven Coanda jet ejectors(detail in Figure A-2b).
Advantages	- confined mixing of hydrocarbons with steam and induced air leads to very efficient steam use - steam wall jets in the Coanda ejectors are much quieter than sonic steam jets from nozzles in typical steam-ring designs
Disadvantes	- expensive construction - openings in mixing section may cause problems with flame stability at low flaring rates in a strong wind
Indair Smokeless Flare (Kaldair - Peabody)	
Construction	- tip as in Figure A-3; principal feature is a tulip-shaped nozzle with low-pressure gas flowing through it and high-pressure gas flowing over it. The h.p. gas remains in a wall jet and follows the curvature of the nozzle wall (Coanda effect) while entraining air. The l.p. gas burns within h.p. gas flame
Advantages	- special purpose flare for producing fields, off-shore rigs, etc., where h.p. gas is available - entrainment of air into h.p. wall jet is relatively silent and efficient, smoke is suppressed, flame luminosity is low

Proprietary and Special Purpose Flare Tips, cont.	
Advantages cont.	- wall jet of h.p. gas cools nozzle wall, high temperature materials are unnecessary - may be operated vertically or horizontally, with significant liquid carry-over
Disadvantages	- cannot be used unless h.p. gas is available - development to replace h.p. gas by steam seems possible, but it may compromise combustion performance since the l.p. gas jet will not be surrounded by a flame
Smoke-Ban Model SVL	
Construction	- tip as in Figure A-4; principal feature is a converging-diverging conical shroud. The flared gas flows from the stack into a center body from which it emerges through slots in radial spokes. Steam nozzles mounted on a steam ring under the shroud induce an air flow over the spokes inside the shroud
Advantages	- large area for mixing the hydrocarbon with air and steam - steam used effectively to induce air flow inside shroud - shroud provides some acoustical shielding for the steam nozzles - large capacity for smokeless flaring
Disadvantages	- expensive construction
Zink Series SA Smokeless Field Flare	
Construction	- tip as in Figure A-5; principal feature is the location of the steam ring under a shroud near the bottom of the flare tip. The steam nozzles are directed into ejector tubes which carry the induced air flow through the tip up to its exit plane where the steam-air flow mixes with the hydrocarbons. A center-steam nozzle is provided below the steam ring.
Advantages	- large area for mixing the hydrocarbon with air and steam - steam used effectively in air ejectors - shroud provides some acoustical shielding for the steam nozzles

Proprietary and Special Purpose Flare Tips, cont.	
Advantages cont.	- large maximum capacity for smokeless flaring - center-steam nozzles gives good performance at low flaring rates
Disadvantages	- expensive construction

TABLE A-2. GROUND LEVEL FLARES (BRZUSTOWSKI, 1976; SEE FOOTNOTE P. A-1)

Construction	- as in Figure A-6; the principal feature is a refractory-lined elevated duct standing inside a louvred enclosure. A number of small burners is mounted on headers and provided with pilot burners using an independent gas supply
Advantages	- cheap and unobtrusive, small ground flares may be built among process units and close to property lines because the flames are not visible. Combustion is smokeless and radiant heating is minimum - many well separated small flames are inherently cleaner than a single large diffusion flame - good design of the individual burners can lead to smokeless burning over a wide turndown ratio - turndown ratio can be increased by staging the gas flow to headers - utilities such as steam or air can be used to burn difficult materials cleanly
Disadvantages	- small capacity, compared to elevated flares. Ground flares of large capacity cover a large land area - require extreme reliability of flame-out protection when burning toxic gases or gases heavier than air since dispersion by wind at the top of a stack is not available in the event of flame-out - in many designs the burners are set up for clean combustion of specific gases; therefore, the flare can be used for routine flaring associated with given process units but not for plant-wide emergency flaring

TABLE A-2. GROUND LEVEL FLARES (BRZUSTOWSKI, 1976; SEE FOOTNOTE P. A-1) (CONTINUED)

Availability	- from most suppliers e.g. - Flaregas Gound Flares - National Airoil NPAC - Zink ZTOF*

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*The Zink ZTOF is a ground flare of large capacity in the form of a tall cylindrical stack of large diameter standing on a grade. With four staged burners mounted at the base, the ZTOF is in many ways similar to an induced-draft furnace. The ZTOF is integrated with an elevated flare through a system of water seals which divert gas to the elevated flare when the ZTOF is operating at capacity. The system offers unobtrusive burning at capacity levels sufficient for routine plant-wide flaring. with the stand-by capacity of an elevated flare for emergency flaring. The one drawback of this system is its high cost.

TABLE A-3. SUPPLIERS OF FLARE EQUIPMENT (BRZUSTOWSKI, 1976; SEE FOOTNOTE, Page A-1)

Flaregas Corporation, 100 Airport Executive Park, Spring Valley, New York 10977, USA

John Zink Company, P. O. Box 7388, Tulsa, Oklahoma 74105, USA

Kaldair Limited - Peabody Engineering Corporation, Sandoz House, 98 The Centre, Feltham, Middlesex TW13 4BH, United Kingdom; and 39 Maple Tree Avenue, Stamford, Connecticut 06906, USA

McGill Incorporated, 5800 West 68th Street, Tulsa, Oklahoma 74107, USA

National Airoil Burner Company, 1284 East Sedgley Avenue, Philadelphia 19134, USA

Samia, S.p.A., 20145 Milano-Via Guerruzzi 27, Italy

Smoke-Ban Manufacturing, Inc., 711 E. Curtis Street, Pasadena, Texas 77502, USA

APPENDIX B

Summary of CARB (California Air Resources Board) Survey

Very little information is available on flare use and the information available is often inaccurate. Two surveys on industrial flare use are available. Klett and Galeski (1976) surveyed use of flare in petroleum refining industry, iron and steel making industry, and the chemical industry. Results from this study have been discussed extensively in Section 2.0.

The California Air Resources Board (CARB) conducted a more recent survey on flare use in California oil refineries (1980). The data has all the disadvantages of a survey but contains useful information on the type of flares used, types of service used in, and steam injection rate. A preliminary summary of the findings of the study follow.

1. Type of Flare. Fifty-five of the sixty-three flares reported are elevated flares and fifty-three were manufactured by John Zink Company. Additional flares were obtained from National Airoil Burners and Flaregas Engineering. Shell uses two ground flares of their own design. Steam injection is the favored means of eliminating smoke with only two flares using venturi inspiration and one using an air blower.
2. Type of Service. The stated use was emergency or blowdown situations. Very few of the 18 companies stated continuous use, although this is common practice.
3. Waste Gas Flow Rate. Since the gas is not metered, this quantity must be estimated. Most companies did not estimate the flow rate; but answers from others seemed to indicate that 100 to 200 million standard cubic feet per year is burned in many flares.
4. Gas Composition. In most cases, this is simply unknown. Typically hydrocarbons are flared (mostly methane, ethane, propane) though some flaring of sulfur species is indicated.
5. Steam Injection Ratio. When needed, steam was used to suppress smoke formation at a rate varying from 0.3 to about 2 lb per lb of hydrocarbon. The spread in steam ratios is unusual since common

practice is to use as little steam as possible as long as smoke is avoided; this minimizes steam costs and avoids quenching the flame.

6. Monitoring of Flare Gas. Rarely is the amount or composition of gas actually measured. Orifice plates may give an indication of some flow rates. Anemometers are used to detect flow in order to regulate steam injection.

7. Adjustment of Steam. Most refineries have manual control of steam while observing the flame either directly or via a television camera. Some ratio control is used, while Chevron uses an automatic optical unit that meters out steam. Union Oil has an anemotherm that sounds an alarm when the flare is used, automatically turns on the steam to a preset ration and waits for an operator to manually lower the rate.

8. Ignition System. Various devices are used to insure ignition in a flare and all companies report that the pilots used are very reliable. Ultraviolet flame detectors and thermocouples hooked up to an alarm are the most common methods. A few refineries use visual means via a television camera to make sure the pilots are lit and the flare is burning.

CARB also requested information concerning any field or "bench" emissions testing but none was received. This is attributed to the difficulty and expense of making such measurements.

APPENDIX C

Quality Assurance Plan

The Quality Assurance Plan describes the procedures which should be used in future programs to verify the quality of the measurement data. Key elements in the plan include the following:

- Administration of Quality Control/Quality Assurance by an independent Quality Assurance Officer.
- Use of documented measurement procedures.
- Application of quality control/quality assurance procedures for each measurement.
- Verification that data precision and accuracy are within program quality objectives.
- Use of necessary corrective action for measurements not meeting quality goals.

Special sampling procedures will be required due to the unique characteristics of flare emissions, including the unconfined exhaust volume. Previous studies of flares have had difficulty in verifying results of exhaust gas measurements. Thus, quality assurance is a very important aspect of the measurements portion of the program. The following subsections discuss the specific procedures which need to be implemented to verify the quality of measurement data.

C.1 Quality Control/Assurance Organization

The Quality Control Assurance activities should be administered by an independent Quality Control Coordinator. The coordinator should have experience in conducting high accuracy measurements, be independent of the program, and report directly to a senior officer of the contractor's company. This arrangement will ensure that the Quality Control/Assurance functions remain objective and will provide for direct involvement of the management of the contractor's company.

The responsibilities of the Quality Assurance Officer should include the following:

- Implement Quality Assurance Project Plan.
- Coordinate all QA/QC activities.
- Review results of QA/QC activities, using statistical procedures and techniques, where appropriate.
- Recommended corrective action to management and program management, as needed.
- Monitor EPA quality assurance activities, to ensure compliance with policies and procedures.

The responsibility of performing specific quality control and quality assurance procedures should be assigned to the project engineering staff conducting the measurements. The Quality Assurance Officer should coordinate these activities, review the results of QC/QA procedures, and recommend corrective action, as needed.

C.2 Tentative Sampling and Analytical Procedures

The objective of measurements should be to determine the combustion efficiency and emissions from flares. The measurements should be performed primarily on scaled-down flares at the contractor's experimental facility so that operating variables can be controlled closely. To quantify flare efficiency and emissions, the measurement should involve determining the mass flow rates of flare inputs and outputs. Table C-1 lists specific parameters to be measured.

Measurements of the exhaust gas flow rates and composition in flare flames present unusual problems compared to other stationary sources due to the following characteristics of flare exhaust streams:

- Unconfined volume of exhaust gas.
- Low velocity of exhaust gas.
- Low exhaust gas concentrations caused by dilution of exhaust gases with the atmosphere.
- Large temporal and spatial variations in exhaust gas concentrations and temperature.

Table C-1. Flare Input and Output Parameters to be Measured.

Input Parameters	Output Parameters
Fuel Flowrate Fuel Composition - carbon - hydrogen - nitrogen - oxygen - heating value Tracer	Exhaust gas velocity and temperature Exhaust gas composition - soot (particulate) - hydrocarbons - carbon dioxide - carbon monoxide - oxygen - SO_2, total sulfur

Special sampling procedures should be used to overcome these problems. The sampling procedures should be designed to measure representative exhaust gas velocities, concentrations and temperatures. The sample collection procedures should include the following:

1. Traversing the cross section of the flare exhaust in a horizontal plane with a single sample probe.
2. Collection of the gases in a hood with an exhaust duct to allow the use of conventional stack sampling procedures.
3. Simultaneous collection of individual, integrated samples using multiple sampling probes.

These procedures should be used to obtain samples representative of the exhaust stream. Sampling should be conducted over extended time periods so that short term variations in gas flow rates and concentrations do not affect the results.

The primary technique to analyze the gas samples should be continuous monitoring instrumentation. Table C-2 lists the instrumentation which might be used. These instruments were selected based on their sensitivity and freedom from interference in measuring the gases of interest. Additional techniques, such as the use of gas chromatography on the integrated samples may also be used, if additional sensitivity is required.

Sampling and analysis to determine soot concentrations will also require special techniques. Soot should be measured by collecting particulates in the exhaust gas followed by gravimetric analysis. Due to the unconfined gas stream, low exhaust gas velocities and large fluctuations in the velocity, it is anticipated that conventional isokinetic particulate sampling will not be possible without the use of an exhaust hood. However, due to the small size of typical soot particles, non-isokinetic sampling should not affect the overall accuracy of the results. It is also anticipated that very elevated gas sample temperatures will be encountered, requiring the use of water-cooled probes and special filter materials for particulate collection. Multiple probe arrangements will be required to allow simultaneous multi-point sampling to minimize total sampling times.

Table C-2. Continuous Gas Analysis Instruments.

Gas Measured	Detection Principle	Manufacturer	Model No.	Full Scale Ranges
Hydrocarbons	Flame Ionization	Beckman	400	0.01 ppm to 2%
Carbon Dioxide	Nondispersive Infrared	Beckman	315B	0 to 5%
Carbon Monoxide	Nondispersive Infrared	Beckman	315A	0-500 ppm
Oxygen	Paramagnetic	Beckman	755	1 to 25%
Sulfur Dioxide	Wet Chemistry	Philips	8850	2.5 - 100 ppm

The recommended measurement procedures are more fully described in Section 5, Measurement Techniques. The use of these special sampling techniques will determine the precision and accuracy of the measurements. Table C-3 shows the tentative goals for the precision and accuracy of the measurements. These goals are based on the sensitivity of the sampling and analytical techniques as well as the data requirements of the program. These goals should be reviewed and finalized during the program, as the results of measurements, application of data, and precision and accuracy of data are analyzed. The quality control and quality assurance procedures described in the following section will be used to determine the measurement, precision and accuracy.

C.3 Quality Control/Quality Assurance Procedure

Each of the flare measurements should be subjected to various quality control procedures. The quality control procedures should be used to verify that 1) the measurements are made according to the prescribed procedures, and 2) the precision of the measurements are known and meet the program goals.

Measurement precision should be evaluated by conducting identical experiments so that the standard deviation of the measurements can be determined. The precision of the measurements should be monitored through the use of control charts displaying the variability of repetitive measurements to allow any decrease in data quality to be identified.

Specific measurement procedures to provide quality control of the data should include the following:

- Operation of the continuous monitoring instruments in accordance with EPA specifications 2 and 3 for continuous monitors.
- Zeroing and spanning each gaseous monitoring instrument with certified calibration gases before and after each test condition.
- Calibration of all test equipment such as gas meters, pilot tubes, thermocouples, and manometers by EPA Reference Method requirements.
- Maintain logs to establish the traceability of all reagents, filters, calibration standards, and test equipment.

Table C-3. Tentative Goals for Precision and Accuracy of Measurements.

Measurement	Measurement Method	Precision	Accuracy
Parameters			
Soot	Gas Filtration, Gravimetric Analysis	< ± 10%	< ± 20%
Hydrocarbons	Continuous Monitoring Instrumentation	< ± 5%	< ± 10%
Carbon Monoxide		< ± 10%	< ± 20%
Carbon Dioxide		< ± 5%	< ± 10%
Oxygen		< ± 5%	< ± 10%
Sulfur Dioxide		< ± 5%	< ± 10%
Fuel Analysis	Gas Chromatograph	< ± 2%	< ± 5%

Quality Assurance procedures should be used to provide an independent assessment of the data accuracy. To ensure that the accuracy of the measurement data meets the program goals, each measurement technique should be verified by at least two independent measurement procedures, where feasible.

One of the key techniques which must be used to verify data accuracy must be calculations of material balances of the flare inputs and outputs. The key measurements in determining flare efficiency and emissions are the concentrations of hydrocarbons, soot, carbon monoxide, and carbon dioxide. A material balance of carbon inputs and outputs will provide an assessment of the accuracy of the following measurements:

- Fuel flow rate.
- Fuel carbon content.
- Exhaust gas flow rate.
- Concentrations of CO_2, CO, hydrocarbons and soot in the exhaust.

Due to the difficulty in obtaining representative samples of the flare exhaust gas, several sampling methods should be used, including probe traversing and hood collection. By using all of these techniques with identical operating conditions, it should be possible to assess the relative accuracy of each method. In particular, the hood collection with conventional analytical techniques should determine average gas concentrations and mass flow rates of the exhaust products. These measurements should allow an assessment of traversing, multiple probe sampling, and the tracer techniques used to determine mass flow rates.

Additional procedures which should be employed could include:

- Analysis of blank samples to determine background interference and contamination.
- Analysis of samples of known concentration (spiked samples).
- Multiple analysis of fuel and gas samples by independent laboratories.
- Analysis of audit samples provided by EPA's Environmental Monitoring Systems/Support Laboratories or IERL-RTP's QA Office.

C.4 Corrective Action

Results of the quality control and quality assurance activities should be continuously monitored by the Quality Assurance Officer. If the results of these activities show that the measurement data do not meet the precision and accuracy goals of the program, the Quality Assurance Officer should recommend corrective action. Potential corrective action should include: 1) documenting the problems, 2) recommending measures to allow some or all of the experimental results to be utilized (with qualification), 3) repeating measurements with minor modifications to the measurement procedures, or 4) recommending major revisions to the sampling and analytical procedures.

APPENDIX D

Emission Factors for Flare Combustion

Translated from the Dutch: "Emissies ten gevolge van de verbranding in afgasfakkels"

Derde Interimrapport van de werkgroep
Afgasfakkels van de Stuurgroep
Emissiefactoren van de Landelijke
Emissieregistratie
Rapport opgesteld door: Ir. H. Bartelds

The emission factors for flare combustion are divided into three groups as shown in Table D-1.

Table D-1. Flare Emission Factors

	Emission Factors					
	A		B		C	
	%	g/GJ	%	g/GJ	%	g/GJ
CO	1		20		Gases are emitted unburned	
C_xH_y	0.1		2			
SO_x	100		100			
NO_x	20	+9	10	+ 4.5		
Soot	0.03		3			

The emission factors of group A are applicable for the combustion of waste gas streams,where the factors from Group B and C are not applicable. In general Group A applies to the undisturbed combustion of controllable waste gas streams, under favorable weather conditions, with gases having a sufficiently high heat content (chemical & sensible), and where soot formation is suppressed through steam injection.

The emission factors of Group B are applied for the combustion of the waste gas stream when:

- The flare throughput is greater than 10% of the design flow, or
- The heat content (chemical & sensible) of the gases lies between 6000 and 10,000 kJ/Nm^3, or

- The wind speed at flare height lies between 20 and 40 m/s, or
- Steam injection is not operable and the flame is visibly sooty.

The emission factors of Group C are applicable for the combustion of waste gas streams when:

- The heat content of the gases is below 6000 kJ/Nm^3, or
- The windspeed at flare height is greater than 40 ms., or
- The pilot flames are not in operation, as a result the flare flame is extinguished.

From the above, it follows that the waste gas streams must be divided into three categories according to which of the three groups of emission factors are applicable. If insufficient information is available in order to decide under which conditions gases will be flared, then use can be made of Table D-2.

Table D-2. Division of Gas Streams

	Division of Gas Streams
Emission Factor A	90%
Emission Factor B	9%
Emission Factor C	1%

Definitions:

The emission factor for CO is the carbon emitted in CO as a percentage of the total carbon in the combustible components of the flared gas.

The emission factor for hydrocarbons (C_xH_y) is carbon content of the emitted C_xH_y expressed as a percentage of the carbon contained in hydrocarbons in the flared gas.

The emission factor for SO_x is the sulfur content of emitted SO_x expressed as a percentage of the sulfur content of the flared gas.

The emission factor for fuel NO_x is the nitrogen content of emitted NO_x expressed as a percentage of the fuel bound nitrogen, exclusive of molecular nitrogen, in the flared gas.

The emission factor for thermal NO_x is the nitrogen emitted as NO_x expressed in grams per Gigajoule (chemical and sensible) of the flared gas.

The emission factor for NO_x is the sum of the emission factors for fuel and thermal NO_x.

The emission factor for the carbon emitted as soot is expressed as a percentage of the carbon contained in combustible components of the flared gas.

Hydrocarbon emissions are expressed in terms of methane equivalent. (1kg C is equivalent to $\frac{16}{12}$ kg C_xH_y)

SO_x is expressed in terms of equivalent SO_2. (1kg S is equivalent to $\frac{64}{32}$ kg SO_2).

NO_x is expressed in terms of equivalent NO_2 (1kg N is equivalent to $\frac{46}{16}$ kg NO_x)

Example:

100 kg/hr of gas are to be flared. The composition of the gas is chosen such that many of the above emission factors are used in the determination of emissions. Factors such as density and calorific value, which in practice may be measured, are calculated.

Table D-3. Composition of Flare Gas and Heat Content of Individual Components

	% vol	kg	MG/m^3
CO	1	1.6	12.0
H_2	50	5.8	12.1
H_2S	1	2.0	23.7
CH_4	15	14.0	37.7
C_3H_8	25	64.2	93.9
N_2	7	11.4	0
NH_3	1	1.0	17.1
Total	100	100.0	

The heat content of the flared gas is the weighted mean of the heat contents of the components; this is 35.7 MJ/m^3. The density of the gas is 0.77 kg/m^3. The combustible components of the gas contain 63.7 kg of carbon.

In the hydrocarbons of the flared gas, there are 63 kg of carbon.

100 kg of gas contains 1.9 kg of sulfur and 0.8 kg of nitrogen (exclusive of molecular nitrogen), and has a heat content of 4.64 GJ.

It is presumed that the gas cannot be subdivided into three groups on the basis of information available from the industrial site, such that use must be made of Table D-2.

$$\text{CO Emission} = 0.9\text{x}63.7\text{x}0.01\text{x}\frac{28}{12} + 0.09\text{x}63.7\text{x}0.20\text{x}\frac{28}{12} + 0{,}01\text{x}1{,}6 = 4.03 \text{ kg}$$

$$C_xH_y \text{ Emission} = 0.0\text{x}63\text{x}0.001\text{x}\frac{16}{12} + 0.09\text{x}63\text{x}0.02\text{x}\frac{16}{12} + 0.01\text{x}63\text{x}1\text{x}\frac{16}{12} = 1.07 \text{ kg}$$

$$SO_x \text{ Emission} = 0.0\text{x}1.9\text{x}1\text{x}\frac{64}{32} + 0.09\text{x}1.9\text{x}1\text{x}\frac{64}{32} + 0.01\text{x}1.9\text{x}0 = 3.76 \text{ kg}$$

$$\begin{aligned} NO_x \text{ Emission} = {} & 0.9\text{x}0.8\text{x}0.2\text{x}\frac{46}{14} + 0.09\text{x}0.8\text{x}0.1\text{x}\frac{46}{14} + 0.01\text{x}0.8\text{x}0 \\ & + 0.9\text{x}4.64\text{x}\frac{9}{1000} + 0.09\text{x}4.64\text{x}\frac{4{,}5}{1000} + 0.01\text{x}4.64\text{x}0 = 0.54 \text{ kg} \end{aligned}$$

$$\text{Soot Emission} = 0.9\text{x}63.7\text{x}0.0003 = 0{,}09\text{x}63{,}7\text{x}0.03 + 0{,}01\text{x}63.7\text{x}0 = 0.19 \text{ kg}$$

Note: The mass of emitted material can no longer be compared directly with the mass of flared gas. A large fraction of the emitted material is derived from atmospheric oxygen and nitrogen. Emitted hydrocarbons, under favorable combustion conditions, are comprised largely CH_4 even though the flared gases comprise also heavier hydrocarbons.

APPENDIX E

Calculation of Flame Shape and Length (Brzustowski, 1976)

The method is based on the cold-flow correlations of concentration in wind-blown hydrocarbon jets.

1. Required information: $\widetilde{M}_j$, ρ_j, u_j, d_j, C_L, u_∞, ρ_∞, $\widetilde{M}_\infty$,
2. Calculate dimensionless lean-limit concentration of fuel

   $$\bar{C}_L = C_L(u_j/u_\infty)(\widetilde{M}_j/\widetilde{M}_\infty)$$

3. Calculate the dimensionless co-ordinate $\bar{S}_L$ of the concentration $\bar{C}_L$ on the axis of the jet and from it the downwind co-ordinate $\bar{X}_L$. This co-ordinate is identified with the location of the flame tip.

   (i) if $\bar{C}_L < 0.5$: $\bar{S}_L = 2.04\ (\bar{C}_L)^{-1.03}$ and $\bar{X}_L = \bar{S}_L - 1.65$

   (ii)if $\bar{C}_L > 0.5$: $\bar{S}_L = 2.51\ (\bar{C}_L)^{-0.625}$

   if $\bar{S}_L > 2.35$ $\bar{X}_L = \bar{S}_L - 1.65$

   if $\bar{S}_L \leq 2.35$ $\bar{S}_L \simeq 1.04\ \bar{X}_L^2 + 2.05\ \bar{X}_L^{0.28}$ 2.5

   In this case $\bar{X}_L$ as a function of $\bar{S}_L$ is shown in Figure A-1

4. Calculate the dimensionless rise $\bar{Z}_L = 2.05\ \bar{X}_L^{0.28}$
5. Calculate the ratio R of the jet momentum flux to the cross-wind momentum flux

   $$R = (\rho_j u_j^2)/(\rho_\infty u_\infty^2)$$

6. Calculate the dimensional co-ordinates of the flame tip relative to the flare tip

   $$z_L = \bar{Z}_L d_j R^{1/2} \qquad x_L = \bar{X}_L d_j R^{1/2}$$

Notes: (i) This procedure should not be used for

$$u_j/u_o > 110$$